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Field Trip B3

Geology of the Island of Grand Manan, New Brunswick: Precambrian to Early Cambrian and Triassic Formations

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J. Gregory McHone [1] and Leslie R. Fyffe [2]

[1] 9 Dexter Lane, Grand Manan, New Brunswick, E5G 3A6
[2] Geological Surveys Branch, New Brunswick Department of Energy and Mines,
PO Box 6000, Fredericton, New Brunswick, E3B 5H1

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Safety

For the sake of personal and group safety, all field trip participants are required to read and abide by the safety related guidelines given below. Although many of them are common sense, we ask for your cooperation to ensure a safe and enjoyable trip for everyone.

- **First Aid/Medical Conditions**: First Aid providers will be identified to the participants at the beginning of the trip. Any participants that are certified First Aiders will be encouraged to identify themselves to the trip leaders. There will be several first aid kits available in the field trip vehicles. As a precautionary measure, field trip participants with medical conditions are encouraged to advise the trip leaders in advance of the trip. This personal medical information will be treated with the strictest confidence.
- **Suitable Footwear and Clothing**: Participants are required to have sturdy footwear with good traction to avoid injury in the trenches and during hiking. Also, because of unpredictable spring weather, participants are to bring proper clothing to protect themselves from the cold (possibly wet) weather (i.e., hat, gloves, rain gear).
- **Rock Hammers**: Please use extreme caution when hammering and be aware of those around you. It is strongly recommended that you wear proper eye protection (i.e., safety glasses or goggles) while hammering and while others are hammering around you. The use of hammers and chisels that are not made for breaking rocks is strictly prohibited because of their potential to splinter and/or break.
- **Slippery Surfaces:** Much of the trip will involve examining outcrops along the shore. Please be aware that these surfaces can be extremely slippery, particularly when wet. Extreme caution should be exercised on smooth, steep outcrop along the shoreline.
- **Falling Rocks**: Several of the stops involve examining exposures along a cliff face that may be unstable. Be sure to look over head for any loose rocks that may be potentially dangerous before getting too close to the outcrop. Climbing the cliff exposures is prohibited as it may be hazardous to you and those around you. If examining the top of a cliff exposure, stay well back from the edge and avoid any activity that may be hazardous to those people that may be at the base of the exposure.
- **Hiking Hazards**: A few of the routes that will be used to access exposures consist of trails through the woods. Please watch your step to avoid tripping on the small pointy stumps. Also, please don’t wander off from the rest of the group, particularly during traverses. If it is absolutely necessary to stray from the group at any time, for the sake of safety, please advise one of the trip leaders before doing so.
- **Transportation**: While the vehicle is in motion, please remain seated and ensure that all of your belongings (especially rock hammers, chisels, and samples) are safely stowed in the back of the van or beneath your seat.

- **Roadside Stops**: The majority of the field trip stops will take place along roads where traffic is minimal. However, depending on time constraints, there may be some stops along the highway and secondary roads where traffic may be a concern. In the event that this occurs, please listen for directions from the trip leaders before crossing the road. Be aware of traffic at all times and always stay well off to the side of the road.
- **IN THE UNLIKELY EVENT OF AN EMERGENCY, CALL 911.** All field trip leaders will be equipped with cellular and/or satellite phones. The location of these phones will be made known to all the participants in case of an accident or injury. It may be necessary to use a pay/private phone in the more remote areas where cellular phone coverage is poor. An emergency response ambulance unit is based near Grand Harbour, and there is a small but good hospital in North Head.

Itinerary

The road logs for the two-day field trip start from the parking lot of the Marathon Inn in North Head, which is about 0.3 km from the ferry wharf, off the highway up Marathon Lane (turn next to the Island Arts Café). Travel is by a chartered bus. On the second day, participants will return to the Marathon Inn or other accommodations before 2:30 pm to gather personal items and to assemble at the foot-passenger shelter at the ferry dock by 3:00 PM. The trip leaders will have tickets for foot passengers. Any participants that have brought their own transportation will need to reserve and pick up their ticket at the window before entering the parking lot. The boat usually loads around 3:10 PM to depart at 3:30 PM. The field trip schedule will be strictly monitored so that participants have time to check out of their lodgings and walk to the ferry dock. Some interesting geological features of the island can be observed as the ferry leaves Grand Manan.

The field trip on the first day will begin at the northern end of the island and work southward. The second day will pick up from the first day's stops. Breakfast is available at several small restaurants in North Head (or at the Marathon Inn if you have made a special meal arrangement). Assemble at the Marathon Inn parking lot to board the bus before 8:30 am. Some field stops are at the mercy of the tides, weather, and waves, which might force changes to the itinerary. Also several stops may be too physically challenging or time-consuming for our group to travel, but descriptions have been included for future reference. Please return at a later date to review the stops.

Also note that field stops will be mixed between Precambrian–Cambrian and Triassic exposures on Grand Manan. Separate road logs for the Mesozoic and pre-Mesozoic stops have been prepared to make it easier to construct this guidebook, and because the sequence of stops during the two days of the trip may need to be varied according to weather, tides, and time constraints. Separate logs should also make it easier during future visits by participants who are interested mainly in one group of rocks or the other.

Part 1: Geology of the Island of Grand Manan

Introduction

This field trip will visit shoreline exposures on the scenic Island of Grand Manan, located in the Bay of Fundy off the southwestern coast of New Brunswick. Grand Manan is unique in Atlantic Canada in displaying the geological features of both the ancient Gondwanan margin of the Paleozoic Iapetus Ocean and the Mesozoic margin of the modern Atlantic Ocean (Fyffe et al. 2011a).

The eastern part of Grand Manan is underlain by complexly deformed sequences of volcanic and sedimentary rocks, the ages of which have only recently been determined by geochronological analyses. The field trip will examine evidence that these dated Mesoproterozoic (?) to earliest Cambrian sequences have characteristics more closely resembling the Gondwanan terrane of Ganderia rather than Avalonia. Following the opening of the Atlantic Ocean, this Ganderian fragment of the former Gondwanan continent was left stranded behind in North America.

Spectacular cliff sections of essentially flat-lying, columnar-jointed and amygdaloidal flows of Triassic basalt, exposed on the western part of Grand Manan, mark the initial break-up of the supercontinent of Pangaea. These ‘flood basalts’ underlie much of the Bay of Fundy, one of several rift basins that formed along the eastern margin of North America prior to the main opening of the Atlantic Ocean. Contact relationships and lithological characteristics of newly recognized sedimentary and basaltic subdivisions within the Triassic sequence exposed on Grand Manan will be examined on the field trip.

Precambrian Terranes of Southwestern New Brunswick

Interpreting the tectonic history of the southeastern margin of the Appalachian Orogen is extremely difficult because strike-slip faulting has juxtaposed several lithotectonic terranes that may have originated in widely separated parts of evolving oceanic basins. In such a geologically complex area it is not possible to arrive at a unique reconstruction of the paleogeography due to the absence of overlapping cover sequences and lack of paleontological or radiometric age control on many of the stratigraphic units. However, plate tectonic models that attempt to explain the accretionary history of the Island of Grand Manan may be constrained to some degree by taking into consideration the geological relationships between various terranes previously recognized on the mainland of southern New Brunswick (Fig. 1).

Three fault-bounded, Precambrian terranes are recognized in southern New Brunswick (Fig. 2) on the basis of their unique stratigraphic and magmatic histories: (1) the Caledonia Terrane, (2) the Brookville Terrane, and (3) the New River Terrane (see Fyffe et al. 2009 and references therein). The Caledonia Terrane and Brookville/New River terranes are considered to be part of the peri-Gondwanan microcontinents of Avalonia and Ganderia, respectively (van Staal et al. 1996, 2012; Hibbard et al. 2006).

The boundary between the Caledonia and Brookville terranes is marked by the Caledonia–Clover Hill Fault. The Brookville and New River terranes are separated by a belt of Early Silurian

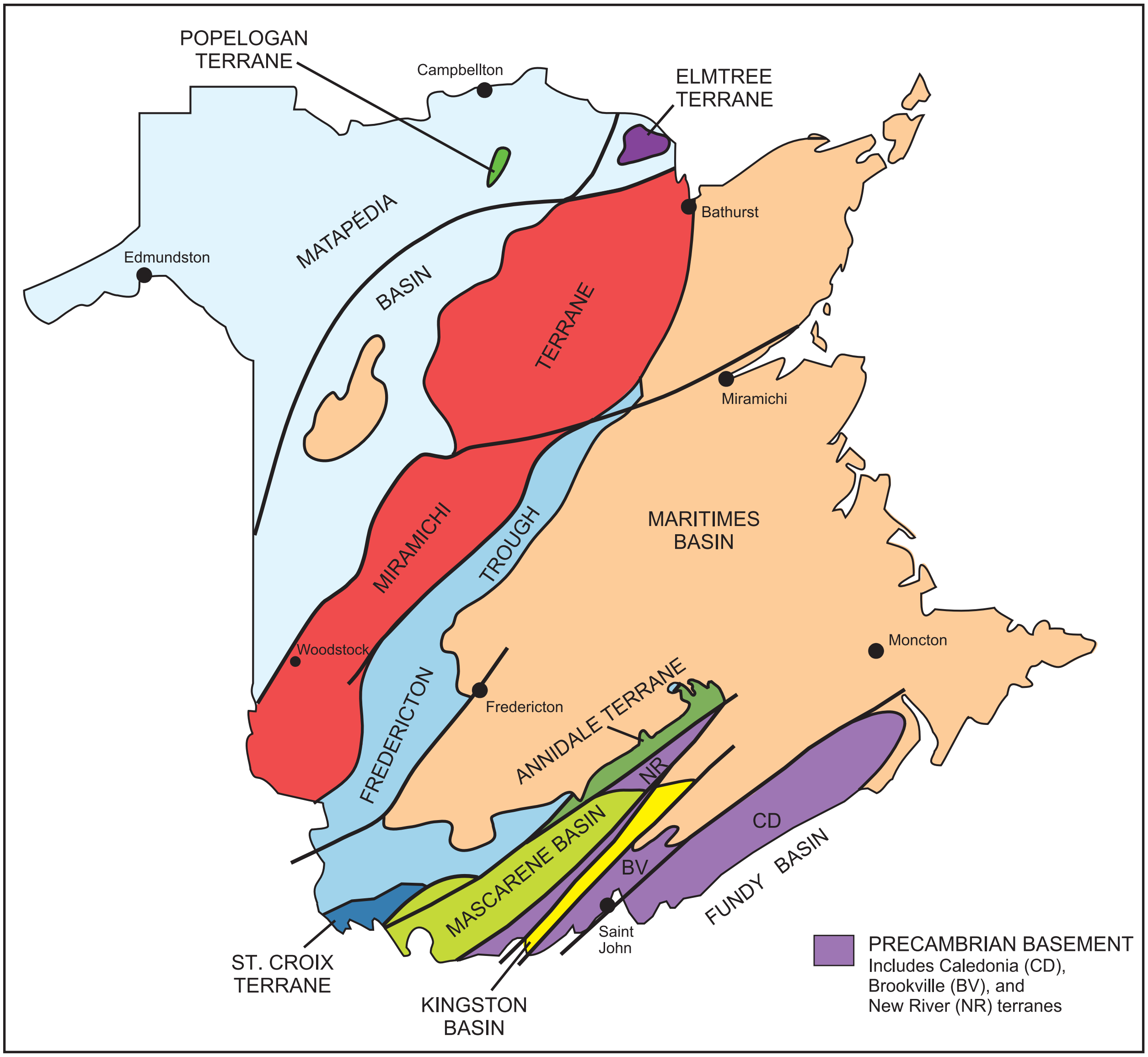


Figure 1. Lithotectonic map of New Brunswick, Canada (after Fyffe et al. 2011b).

volcanic rocks of the Kingston Basin (Fyffe et al. 1999; Barr et al. 2002). The New River Terrane lies north of the Kingston Basin and is separated from it by the Belleisle-Beaver Harbour Fault (Johnson and McLeod 1996). Early to Late Silurian volcanic rocks of the Mascarene Basin overlie much of the Precambrian New River Terrane. The Brookville Terrane (White and Barr 1996) lies south of the Kingston Basin and is separated from it by the Kennebecasis-Pocologan Fault.

The Brookville and New River terranes in mainland southern New Brunswick are considered herein to represent the trailing passive margin of a distinctive Ganderian microcontinent that rifted from Gondwana in the early Paleozoic. This interpretation is based on the shared presence of thick, Neoproterozoic to early Paleozoic, Ganderian-like, quartz-rich sandstone sequences, which are absent in Avalonia (Barr and Raeside 1989; van Staal et al. 1996, 2012; Hibbard et al. 2006; Fyffe et al. 2009). Such Ganderian, continental margin sedimentary rocks on Precambrian basement appear to have been preserved only in the New Brunswick segment of the Appalachians.

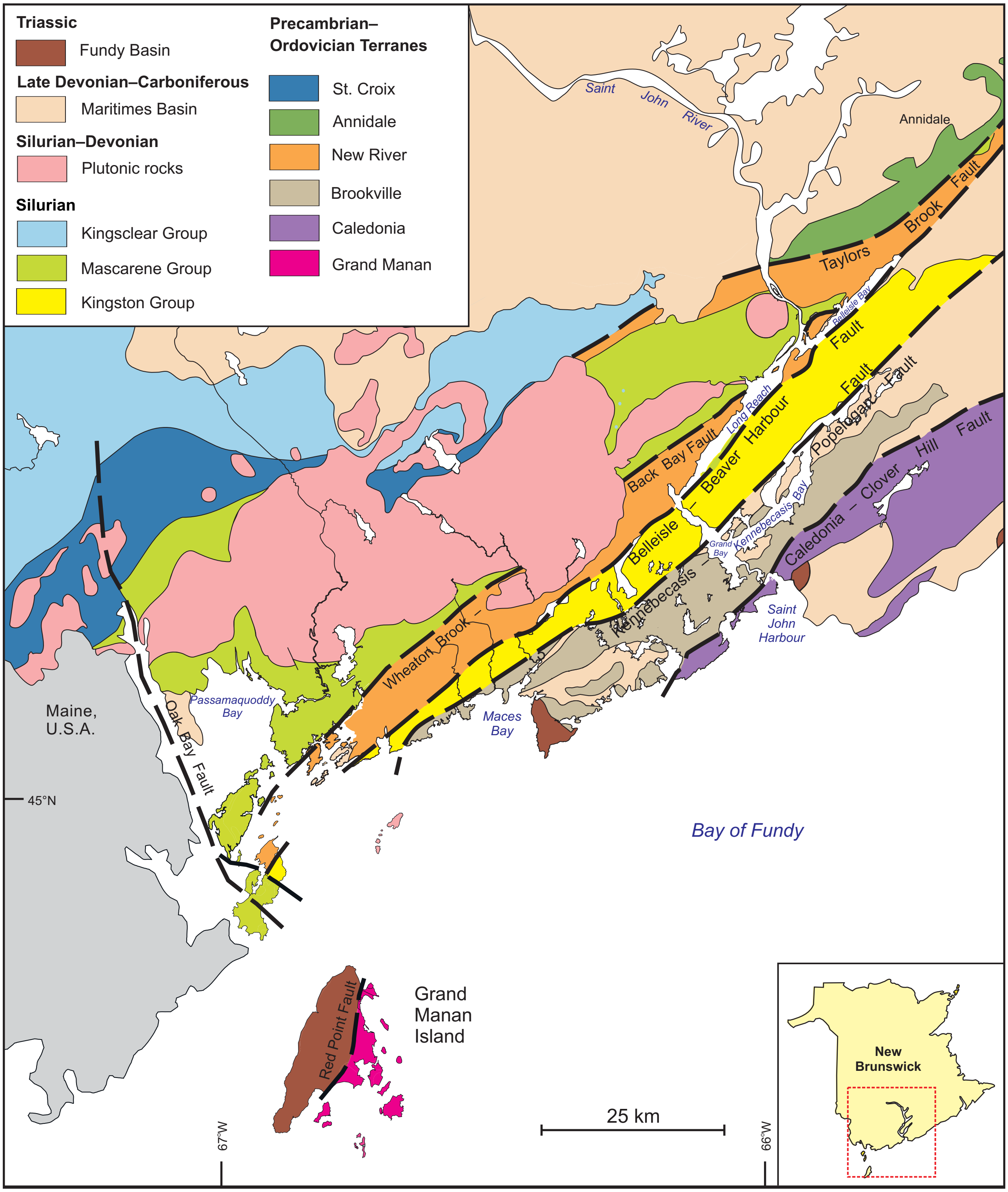


Figure 2. Lithotectonic terranes in southwestern New Brunswick (modified from Fyffe et al. 2011b).

Recently published U/Pb magmatic zircon age determinations (Barr et al. 2003a, Black et al. 2004; Miller et al. 2007; and Fyffe et al. 2009) have confirmed a Precambrian age for much of the bedrock on the eastern side of the Island of Grand Manan (Fig. 3) as previously suggested by Alcock (1948). These dates together with the presence of carbonate and quartz-rich sedimentary

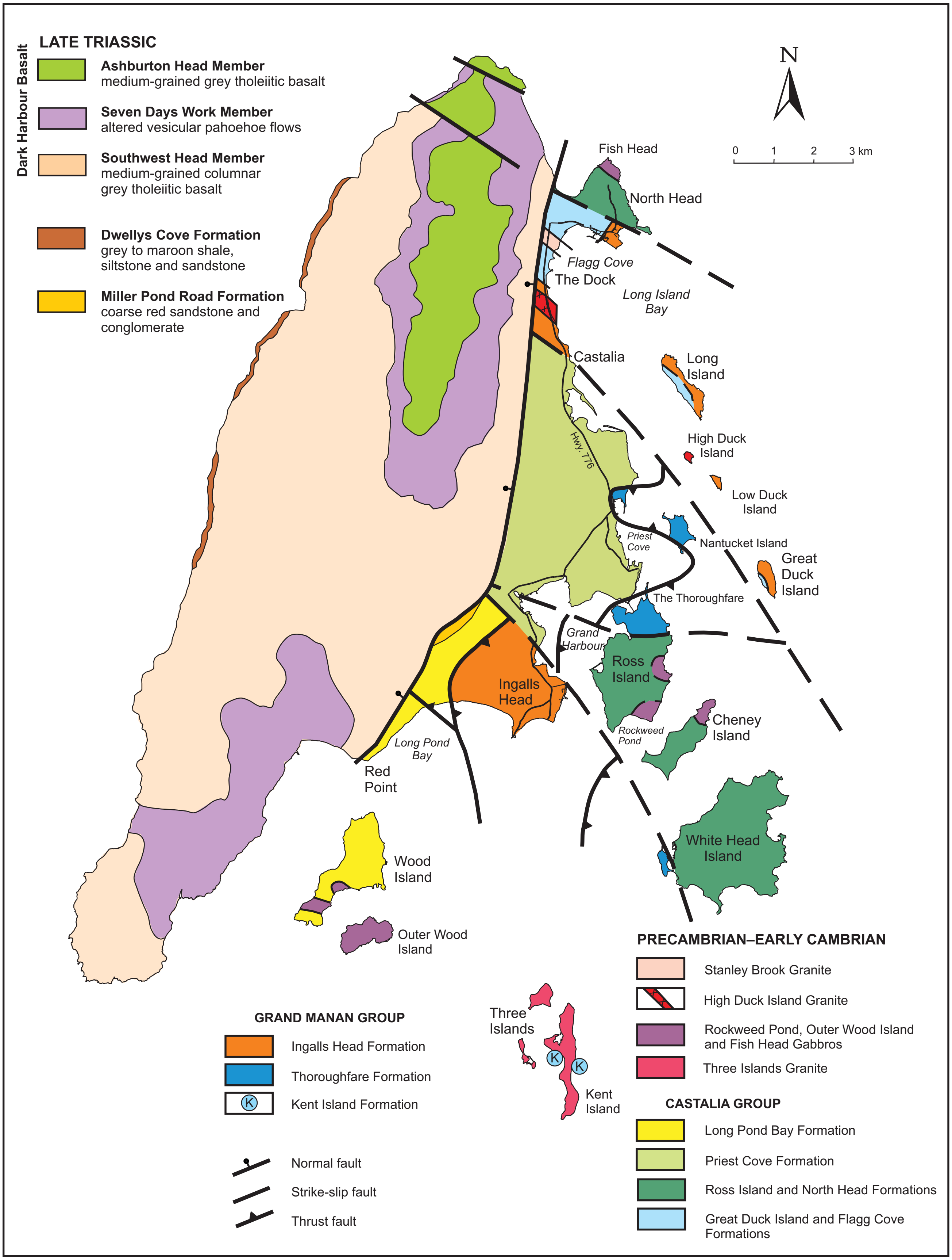


Figure 3. Bedrock geology map of the Island of Grand Manan (simplified from Fyffe et al. 2011b).

rocks suggest possible lithotectonic linkages of Grand Manan to the Ganderian Brookville and New River terranes on the New Brunswick mainland (Fig. 2). The pre-Triassic rocks on Grand Manan that are similar to those of the Brookville and New River terranes are offset from those on the mainland by the sinistral Oak Bay Fault (Miller et al. 2007; Fyffe et al. 2009).

The Annidale, St. Croix, Miramichi, Elmtree, and Popelogan terranes, all of which lie to the northwest of the New River Terrane (Fig. 1), represent progressively younger Paleozoic arcs and backarc basins that developed on the active margin of Ganderia (van Staal and Fyffe 1995; van Staal et al. 1996, 2009; Fyffe et al. 2011b; Johnson et al. 2012). These particular arc/backarc terranes do not extend into the southwestern coastal region of New Brunswick. Silurian sedimentary rocks of the Fredericton Trough in southern and central New Brunswick, and Late Ordovician to Early Devonian sedimentary and volcanic rocks of the Matapédia Basin in northwestern and northern New Brunswick were deposited in successor basins that developed on Ganderia after the cessation of Middle Cambrian to Middle Ordovician volcanic arc activity related to closure of the main tract of the Iapetus Ocean.

Caledonia Terrane

Precambrian rocks of the Caledonia Terrane on the New Brunswick mainland are divided into the Late Neoproterozoic Broad River and Coldbrook groups.

The Broad River Group comprises a sequence of mainly intermediate to felsic crystal tuffs, lithic-crystal tuffs, and tuffaceous sedimentary rocks that yielded a U/Pb zircon age of 613 ± 2 Ma. Associated comagmatic plutonic rocks (Point Wolfe River Suite) range in age from 625 ± 5 Ma to 616 ± 3 Ma (Bevier and Barr 1990; Barr and White 1999). Rocks of the Broad River Group are found only in the Caledonian Highlands to the east of Saint John and thus do not occur in the field guide area.

The Coldbrook Group consists of intermediate to felsic lithic tuff and breccia, crystal tuffs, and flows, interbedded with laminated, green tuffaceous siltstone and maroon to red arkose, sandstone, and siltstone. Tuffs from the Coldbrook Group yielded U/Pb zircon ages ranging from 559 ± 1 Ma to 548 ± 1 Ma. Associated comagmatic plutons of the Bonnell Brook Suite range in age from 557 ± 3 Ma to 550 ± 1 Ma (Bevier and Barr 1990; Barr et al. 1994, 2003b; Barr and White 1996a, 1996b,1999).

Volcanic rocks of both the Avalonian Broad River and Coldbrook groups are interpreted on the basis of geochemistry to have formed in a continental magmatic arc setting (Currie and Eby 1990; Barr and White 1996a), although an extensional setting has also been proposed for the latter (Barr and White 1996b). They are similar in age and tectonic setting to rocks on the trailing margin of Ganderia (Brookville and New River terranes) but are isotopically less evolved (Whalen et al. 1994, 1996a, 1996b; Barr et al. 1998; Samson et al. 2000; Satkoski et al. 2010).

The Precambrian basement rocks of the Caledonia Terrane are overlain by Cambrian to Early Ordovician platformal sedimentary strata of the Saint John Group (Hayes and Howells 1937; Alcock 1938; McLeod and McCutcheon 1981; Tanoli and Pickerill 1988, Landing et al. 1998; Palacios et al. 2011; Barr et al. 2012).

Brookville Terrane

Precambrian rocks of the Brookville Terrane on the New Brunswick mainland comprise the Green Head Group, Brookville Gneiss, Dipper Harbour Group, and Golden Grove Plutonic Suite.

The Mesoproterozoic (?) to Neoproterozoic platformal rocks of the Green Head Group include marble, which locally contains stromatolites, and lesser quartzose sandstone of the Ashburn Formation; and discordantly overlying siltstone, quartzose sandstone, quartzite pebble conglomerate, and limestone breccia of the Martinon Formation. Both of these formations represent older passive-margin sequences unrelated to Iapetus closure (Hofmann 1974; Nance 1987; Currie 1991; White and Barr 1996). The Ashburn and Martinon formations cannot be older than 1.228 ± 0.003 Ga and 602 ± 8 Ma, respectively, according to their youngest contained detrital zircon populations (Barr et al. 2003b; Fyffe et al. 2009).

The Brookville Gneiss is a unit of paragneiss and orthogneiss that is in sheared contact with the Green Head Group; the orthogneiss was emplaced at 605 ± 3 Ma (U/Pb zircon date) and was metamorphosed to upper amphibolite facies at 564 ± 6 Ma (Bevier et al. 1990; Dallmeyer et al. 1990; Nance and Dallmeyer 1994).

Volcanic rocks of the Dipper Harbour Group occur in a fault panel that was thrust over Green Head carbonate strata along the Bay of Fundy coast. Felsic flows and crystal tuffs (Round Meadow Cove Formation) from the Dipper Harbour Group yielded a Late Neoproterozoic U/Pb zircon age of 553 ± 3 Ma (Currie and McNicoll 1999; White et al. 2002; Barr et al. 2003c).

Plutonic rocks of the Golden Grove suite have intruded the Green Head Group. They range from late Neoproterozoic to Early Cambrian (548 ± 2 Ma to 528 +1/–3 Ma) and possess mainly calc-alkaline, continental-arc geochemical signatures (Whalen et al. 1994; Eby and Currie 1996; White and Barr 1996; Currie and McNicoll 1999; White et al. 2002; Barr et al. 2003c).

The Precambrian basement rocks of the Brookville Terrane are locally overlain by Cambrian platformal quartzose sandstone of the Saint John Group (Hayes and Howell 1937; Alcock 1938; Westrop and Landing 2000).

New River Terrane

The New River Terrane of mainland New Brunswick is the most outboard of the Precambrian terranes with respect to the Paleozoic Iapetus Ocean (Fig. 1) and the only one known to contain remnant elements of Iapetan, subduction-related, arc system. The Late Neoproterozoic Lingley Plutonic Suite and Blacks Harbour Granodiorite are the oldest rocks in the New River Terrane. The Lingley suite includes granodiorite, red leucogranite, and quartz–feldspar porphyry (Currie 1987; Johnson 2001; Johnson and Barr 2004). U/Pb zircon ages of 625 ± 2 Ma and 629 ± 1.0 Ma have been obtained from the granodiorite and granite, respectively (Currie and McNicoll 1999). The Blacks Harbour Granodiorite yielded a U/Pb zircon age of 622 ± 2 Ma, essentially the same age as the Lingley suite (Barr et al. 2003c; Bartsch and Barr 2005).

Late Neoproterozoic to earliest Cambrian volcanic rocks in the New River Terrane are included in the Belleisle Bay Group and are associated with comagmatic intrusive rocks, all of which are in faulted contact with the older (629–625 Ma) plutons. The Late Neoproterozoic rocks in the Belleisle

Bay Group are a sequence of felsic flows and pyroclastic tuffs that yielded U/Pb zircon ages of 554 ± 3 Ma and 554 ± 6 Ma (McLeod et al. 2003). Comagmatic granodiorite and subordinate granite of the Ragged Falls Granodiorite yielded U/Pb zircon ages of 553 ± 2 Ma and 555 ± 10 Ma, respectively (Currie and Hunt 1991; Johnson and McLeod 1996; Johnson 2001; McLeod et al. 2003). A younger sequence of latest Neoproterozoic to earliest Cambrian volcanic rocks within the Belleisle Bay Group comprises felsic flows and pyroclastic tuffs interbedded with arkosic sandstone and red and green siltstone, and mafic breccias (McLeod 1995; Johnson and McLeod 1996; Johnson 2001). A felsic flow and tuff from this sequence yielded earliest Cambrian U/Pb zircon ages of 539 ± 4 Ma and 541 ± 3 Ma (Barr et al. 2003c; Bartsch and Barr 2005; Johnson et al. 2012).

Fossiliferous Cambrian strata traditionally assigned to the Saint John Group occur in fault-bounded slivers in the southwestern part of the New River Terrane (Greenough et al. 1985; Johnson 2001; Landing et al. 2008). Early to Middle Cambrian trilobites occur in limestone beds in the middle and upper sequences (Helmstaedt 1968; Landing et al. 2008). The mafic rocks have an evolved, continental tholeiitic geochemical signature (Greenough et al. 1985).

Cambrian quartzose sedimentary rocks of the Almond Road Group overlie the latest Neoproterozoic to earliest Cambrian rocks of the Belleisle Bay Group in the northeastern part of the New River Terrane (Fyffe et al. 2011b; Johnson et al. 2012). The lower part of the Almond Road Group comprises orthoquartzite and quartzite-pebble conglomerate, and the upper part comprises quartzose sandstone and dark grey shale, and minor mafic volcanic rocks. The Almond Road Group is no younger than the cross-cutting West Scotch Settlement Porphyry, which yielded an Early Ordovician U/Pb zircon age of 475 ± 2 Ma (S.C. Johnson, unpublished data).

Cambrian quartz-rich sedimentary rocks are also present along the northwestern margin of the southwestern part of the New River Terrane. This Middle Cambrian sequence is included in the Ellsworth Group in New Brunswick, derived from the term ‘Ellsworth Schist’, the name used for similar volcanic rocks in adjacent Maine (Schultz et al. 2008; Fyffe et al. 2009). In New Brunswick, the Ellsworth Group comprises interbedded quartzose sandstone and quartzite-pebble conglomerate in the lower part; and felsic flows, tuffs and breccia, and fine-grained, iron-rich volcaniclastic sandstone and siltstone in the upper part. Felsic volcanic breccia near the top of the sequence yielded a U/Pb zircon age of 514 ± 2 Ma (Johnson and McLeod 1996; Johnson 2001; McLeod et al. 2003). The volcanic rocks range in composition from andesite to rhyolite and represent the remnants of an Iapetan backarc basin that was accreted to the New River Terrane during the Early Paleozoic Penobscot Orogeny (Fyffe et al. 2011b; Johnson et al. 2012).

Tectonic Overview

The geological evolution of the Appalachian Orogen be understood in terms of the assemblage and break-up of three supercontinents–Rodinia, Gondwana, and Pangea. Amalgamation of a number of continental fragments, which followed the breakup of the supercontinent of Rodinia and opening of the Pacific Ocean, resulted in the formation of the supercontinent of Gondwana by the end of the Neoproterozoic (Dalziel 1997). The protracted magmatic, metamorphic, and tectonic events related to the closure of ocean basins leading to the assemblage of Gondwana have been termed ‘Pan African’ by Kennedy (1964) and more recently as ‘Brasiliano/Pan African (da Silva et al. 2005). Laurentia later broke away from Gondwana with the opening of the Iapetus and Rheic oceans in the Early Paleozoic (Nance and Linnemann 2008; van Staal et al. 2012). Closure of these two Paleozoic oceans led to the amalgamation of Gondwana with Laurentia to form the supercontinent of Pangea by the end of the Carboniferous (Murphy et al. 1999). The subsequent break-up of Pangea began with rifting in the Late Triassic and the opening of the Atlantic Ocean by the Early Jurassic (Wade et al. 1996; Olsen 1997).

In New Brunswick, five Appalachian orogenic cycles contributed to the accretion of lithotectonic terranes onto the Gondwanan and Laurentian margins during closure of the Iapetus Ocean. These include the Early Ordovician Penobscot Orogeny, the Late Ordovician Taconic Orogeny, the Silurian Salinic Orogeny, the latest Silurian to earliest Devonian Acadian Orogeny, and Carboniferous Alleghenian Orogeny (see Fyffe et al. 2011b and references therein).

During the Taconic orogeny, Iapetan island arcs in northwestern New Brunswick (Popelogan Terrane, Fig. 1) and adjacent Quebec were accreted to the Laurentian margin of North America. Opening of an Iapetan backarc basin in southern New Brunswick (Annidale Terrane, Fig. 1, 2) during the Late Cambrian to Early Ordovician (Johnson et al. 2012) overlapped in time with the initial opening of the Rheic Ocean and separation of Ganderia and Avalonia from the Gondwanan continental margin (van Staal et al. 2012). Subsequent closure of the Annidale backarc basin in the Early Ordovician juxtaposed the New River and Miramichi terranes during the Penobscot Orogeny.

Closure of the Tetagouche backarc basin in northeastern New Brunswick during the Salinic Orogeny led to the accretion of the oceanic (Elmtree Terrane, Fig. 1) and continental (Miramichi Terrane, Fig. 1) parts of the backarc to Laurentia (van Staal et al. 2009; Fyffe et al. 2011b), effectively closing the Iapetus Ocean by the Late Silurian. Closure of a marginal seaway in southern New Brunswick accreted Avalonia (Caledonia Terrane) to Laurentia during the Acadian Orogeny. Low-angle thrusting along the Bay of Fundy coast during the Carboniferous Alleghenian Orogeny is related to closure of the Rheic Ocean to the south of Avalonia.

Pan African-Braziliano Orogenic Activity

Both Avalonia (Caledonia Terrane) and Ganderia (Brookville/New River terranes) had active margins from 630 Ma to 610 Ma, when they were still connected to the Amazonian continental margin of Gondwana (van Staal et al. 2012). Arc magmatism in Ganderia was possibly interrupted by ridge subduction or backarc extension at 605 Ma; this would account for the observed granitic magmatism and high-temperature–low-pressure metamorphism, evidence of which is preserved in the Brookville Gneiss (Bevier et al. 1990; Fyffe et al. 2009). Renewed arc magmatism, beginning around 555 Ma, took place along the Ganderian margin during the Late Neoproterozoic to Early Cambrian (White et al. 2002; Fyffe et al. 2009, 2011b). The initial renewal of Ganderian arc magmatism is essentially coincident with the 560 Ma to 550 Ma magmatism recorded in the Coldbrook Group of the Avalonian Caledonia Terrane in New Brunswick, although the latter magmatism may have been generated in an extensional tectonic setting (Barr and White 1996b, 1999). Renewed arc magmatism was more or less continuous in the Brookville Terrane until at least 528 Ma, where it was locally accompanied by deformation and metamorphism (White and

Barr 1996). Arc magmatism ceased earlier in the New River Terrane, in the earliest Cambrian at 540 Ma; there, it was followed by a period of quiescence represented by the accumulations of thick, Ganderian-like sedimentary sequences of the Cambrian Almond Road Group and Matthews Lake Formation, and platformal sequences of the Saint John Group.

Penobscot Orogeny

No magmatism was recorded in Ganderia for a period of 10 million years following the cessation of Precambrian orogenic activity. Arc volcanism resumed at the near the beginning of the Middle Cambrian with the eruption of volcanic rocks of the Mosquito Lake Road Formation at 514 ± 2 Ma onto Precambrian basement rocks of the New River Terrane (Johnson and McLeod 1996). Subsequent opening of the Annidale backarc basin behind the arc led to the separation of the Miramichi Terrane from the New River Terrane (Fig. 1). A felsic dome associated with the opening of this backarc basin has been dated at 493 ± 2 Ma (McLeod et al. 1992). The two separated parts of Ganderia (New River and Miramichi terranes) were rejoined in the Early Ordovician (late Tremadocian) following obduction of oceanic crust flooring the Annidale backarc basin. The timing of this closure is constrained by the intrusive age of 479 ± 2 Ma for the Stewarton Gabbro (Johnston et al. 2012), which was emplaced along the boundary between Annidale and New River terranes. The timing of the deformational events associated with the accretion of the Annidale Terrane to the New River Terrane in southern New Brunswick coincides with that of the Penobscot Orogeny, first recognized by Neuman (1984) in adjacent Maine.

Acadian Orogeny

The Acadian Orogeny in southern New Brunswick may have been initiated by subduction and closure of a narrow seaway situated between Avalonia (Caledonia Terrane, Fig. 2) and Ganderia (Brookville and New River terranes, Fig. 2) (van Staal et al. 2009, 2012). Evidence of northwesterly directed subduction is preserved principally in the Kingston and Mascarene basins (Eby and Currie 1993; Barr et al. 1997, 2002; Fyffe et al. 1999). The Kingston Basin is characterized by an abundance of Silurian calc-alkaline magmatic rocks (442–435 Ma) referred to as the Coastal Arc. These arc rocks were intruded by tholeiitic mafic dykes, indicating that the arc was extensional, consistent with the presence of coeval backarc volcanic rocks in the adjacent Mascarene Basin. On its southern margin, the Kingston Basin contains high-pressure metamorphosed sedimentary and volcanic rocks of the Pocologan Metamorphic Suite, interpreted to mark a cryptic suture zone between Avalonia and Ganderia (White et al. 2006). Underthrusting of the Avalonian plate beneath Ganderia is consistent with the location of backarc rocks in the Mascarene Basin to the northwest of the Coastal Arc.

Acadian structures in southern New Brunswick are characterized by a combination of northwestward-directed reverse faults, generally upright folds, and sinistral and dextral strike-slip faults (Léger and Williams 1986; Doig et al. 1990; Nance and Dallmeyer 1993; Park et al. 1994; van Staal and de Roo 1995; van Staal et al. 2009). Migration of the Acadian deformational front progressively toward the northwest across the Appalachian Orogen has been attributed to flat-slab subduction and prolonged underthrusting of Avalonia beneath Laurentia (Murphy et al. 1999).

Alleghenian Orogeny

Subsequent closure of the Rheic Ocean to the south of Avalonia united Gondwana with Laurentia to form the supercontinent of Pangea. In the central and southern Appalachians, this late Paleozoic continent–continent collision event is referred to as the Alleghenian Orogeny and is characterized by widespread folding, metamorphism, and overthrusting on a major décollement. In contrast, contemporaneous deformation in the northern Appalachians is apparent only in Carboniferous strata caught up in local transpressive zones along the Bay of Fundy coast (Rast and Grant 1973; Rast 1984; Nance 1985; Nance and Warner 1986).

Opening of the Atlantic Ocean

Late Triassic rifting of the Pangaean supercontinent preceded the opening of the central Atlantic Ocean in the Early Jurassic. This initial rifting is recorded by the deposition of terrestrial redbeds and emplacement of flood basalts in fault-bounded basins along the Bay of Fundy, at Point Lepreau, and on the Island of Grand Manan (Nadon and Middleton 1984, 1985; Olsen 1997; McHone 2011). The separation of the Americas from Europe and Africa by widening of the Atlantic Ocean left the former peri-Gondwanan microcontinents of Ganderia and Avalonia stranded on the eastern coast of North America. Late Triassic to Early Jurassic sediments and basalts in the Bay of Fundy region comprise the Fundy Group (Wade et al. 1996), which are part of the Newark Supergroup of eastern North America (Olsen 1997).

Precambrian to Early Cambrian Geology of the Island of Grand Manan

The Precambrian to Early Cambrian stratified rocks on the Island of Grand Manan and nearby islands (Fig. 3) consist mainly of quartzose and carbonate sedimentary rocks, and volcanic and reworked volcaniclastic sedimentary rocks. Metamorphic grade generally does not exceed greenschist facies, and in many places, primary sedimentary and igneous textures are well preserved. Contacts between the various pre-Mesozoic formations recognized on Grand Manan are generally covered or faulted making it difficult to determine the original stratigraphic order of some of these sequences (McLeod et al 1994; Fyffe and Grant 2001). A recent U/Pb geochronological program on magmatic and detrital zircons from these rocks, carried out jointly by the New Brunswick Geological Survey, Acadia University, and the Geological Survey of Canada, has done much to clarify some of these stratigraphic relationships (Barr et al. 2003a; Black et al. 2004; Miller et al. 2007; and Fyffe et al. 2009).

Formational terminology follows that of Fyffe et al. (2011a). Based on exposed and inferred stratigraphic relationships, depositional environments, and U/Pb ages, the formations recognized on Grand Manan and nearby islands are divided into the Mesoproterozoic to Neoproterozoic Grand Manan Group (probable minimum age of 618 ± 3 Ma), and the younger Neoproterozoic to Early Cambrian Castalia Group (probable minimum age of 539 ± 3 Ma). The Grand Manan Group comprises the Kent Island, The Thoroughfare, and Ingalls Head formations; the Castalia Group comprises the Great Duck Island, Flagg Cove, Ross Island, North Head, Priest Cove, and Long

Pond Bay formations. The contact between the two groups is generally faulted (interpreted as a thrust fault) but an unconformity is locally preserved on Great Duck and Long islands (Fig. 3).

Grand Manan Group

The mutual stratigraphic relationships of the Kent Island, The Thoroughfare, and Ingalls Head formations of the Grand Manan Group remain uncertain although all are older than the Late Neoproterozoic to Early Cambrian Castalia Group. White to buff marble of the Kent Island Formation is only exposed on Kent Island, located 7 km south off the southern coast of the Island of Grand Manan. The marble, which occurs as large blocks in the Neoproterozoic (611 ± 2 Ma) Three Islands Granite (Barr et al. 2003a), has been correlated with the platformal, stromatolitic carbonates of the Ashburn Formation of the Green Head Group by Alcock (1948), and therefore could be as old as Mesoproterozoic.

The Thoroughfare Formation is best exposed on the northern end of Ross Island on the southeastern coast of Grand Manan (The Thoroughfare separates Ross Island from the Island of Grand Manan, Fig. 3). The Thoroughfare Formation is composed of very thick- to thin-bedded, locally cross-bedded, white to light grey quartzite interstratified with grey to black carbonaceous shale (Fig. 4). The thick units of massive quartzite (Fig. 5) are interpreted to represent prograding fan lobes sourced from winnowed shelf sand during a fall in sea level. Detrital zircons from the quartzite indicate that The Thoroughfare Formation is no older than 1.425 ± 0.098 Ga (unpublished data). Rare marble and abundant quartzite clasts occur in a cobble conglomerate (a possible correlative of the Great Duck Island Formation, see below) on Gannet Rock to the south of the Island of Grand Manan. These marble and quartzite clasts may be sourced from the Kent Island and The Thoroughfare formations, suggesting similarity in the ages of the two formations (Miller et al. 2007).

The correlation of the marble comprising the Kent Island Formation with the stromatolitic carbonates of the Green Head Group invites a comparison to the Brookville Terrane on the New Brunswick mainland. It is possible that the Kent Island marble and The Thoroughfare quartzite, which both may be as old as Mesoproterozoic, represent basement to the latest Neoproterozoic to earliest Cambrian volcanic and sedimentary rocks on the Island of Grand Manan.

The Ingalls Head Formation is well exposed on Ingalls Head along the southeastern coast of Grand Manan and on Long Island off the northeastern coast of Grand Manan (Fig. 3). The Ingalls Head Formation comprises a sequence of intermediate tuff, commonly containing maroon lenses of magnetic chert (Fig. 6), interstatified with lesser volcanic breccias, felsic flows (Fig. 7), and purple laminated mudstone (Fyffe et al. 2011a). A felsic flow on Ingalls Head yielded a Neoproterozoic U/Pb zircon age of 618 ± 3 Ma (Barr et al. 2003a; Miller et al. 2007). Limited chemical analyses (Table 1, on p. 27) indicate that the intermediate volcanic rocks range from andesite to dacite in composition and have a calc-alkaline affinity (Pe-Piper and Wolde 2000; Black et al. 2004; Black 2005).

The similar age of the volcanic rocks of the Ingalls Head Formation (618 ± 3 Ma) on the Island of Grand Manan to the offshore Three Islands Granite (611 ± 2 Ma) suggests a shared geological

Figure 4. Tightly folded, thin-bedded quartzite and shale of The Thoroughfare Formation at the north end of Ross Island.

Figure 5. Thick-bedded quartzite of The Thoroughfare Formation at the north end of Ross Island.

Figure 6. Schistose andesitic tuff of the Ingalls Head Formation at Ox Head, Island of Grand Manan. Note the maroon lenses of magnetic chert in the tuff.

Figure 7. Spherulitic rhyolite flow of the Ingalls Head Formation at Long Pond on Long Pond Bay, Island of Grand Manan.

history with the sedimentary rocks of the Kent Island and The Thoroughfare formations of the Grand Manan Group. The ages of the Ingalls Head Formation and Three Islands Granite are similar to volcanic (613 ± 2 to 600 ± 1 Ma) and plutonic rocks (625 ± 5 to 616 ± 3 Ma) of the Broad River Group in the Caledonia Terrane of southeastern New Brunswick but no iron-rich cherts have been reported from the latter (Barr and White 1999). Plutonic rocks dated from 629 ± 1 to 622 ± 2 Ma occur in the northeastern part of the New River basement block (Currie and McNicoll 1999; Barr et al. 2003b).

Castalia Group

The post-600 Ma strata of the Castalia Group are divided into six formations (Fig. 3): two that are sedimentary (Great Duck Island and Flagg Cove), and four that are volcanic-rich (Priest Cove, Ross Island, North Head, and Long Bay Pond). The contacts between formations within the Castalia Group are not exposed and assumed to be faulted. A thrust contact between the Priest Cove Formation and presumably older Grand Manan Group is exposed on the western shore of The Thoroughfare. Although contacts of the Castalia Group with the older volcanic rocks of the Grand Manan Group are generally faulted, an unconformity is preserved on Long and Great Duck islands.

The Great Duck Island Formation, exposed on the western shore of Great Duck and Long islands, and at The Dock on the eastern coast of Grand Manan, is sequence of medium-bedded, maroon and olive green sandstone and silty shale interstratified with thick-bedded, light grey to maroon quartz-pebble conglomerates. The conglomerate is massive and matrix-supported, locally cross-bedded, and likely represents debris flows deposited in channels on the inner part of a submarine delta. On Great Duck Island, the pebble-to-cobble conglomerate of the Great Duck Island Formation contains volcanic clasts clearly derived from an immediately underlying plagioclase-phyric mafic flow of the Ingalls Head Formation (Fig. 8). The conglomerate is, therefore, no older than 618 ± 3 Ma, the eruptive age of the Ingalls Head volcanic rocks. A coarser conglomerate, exposed at The Dock on the Island of Grand Manan (Fyffe et al. 2011a), contains abundant quartzite clasts likely derived from The Thoroughfare Formation of the Grand Manan Group, and is therefore correlated with the Great Duck Island Formation (Fig. 9). Although outcrop along the shoreline is not continuous, the conglomerate-rich sequence, which youngs to the northeast at the Dock, appears to grade up-section into the sandstone-rich sequence of the Flagg Cove Formation exposed further to the north in Flagg Cove.

The Flagg Cove Formation, exposed at Flagg Cove in Long Island Bay along the eastern coast of Grand Manan near the ferry dock (Fig. 3), comprises thin- to medium-bedded, graded, light grey quartzose sandstone and minor quartzite-pebble conglomerate interstratified with light green to dark grey silty shale (Fig. 10, 11). The trace fossil *Planolites* has been identified on bedding surfaces along Stanley Beach (Ron Pickerill, pers. comm.). The sequence is interpreted to be a deeper water facies of the conglomeratic Great Duck Island Formation and to have been deposited in a distal marine fan environment. The stratigraphic age of the Flagg Cove Formation is constrained to be no older than 574 ± 7 Ma on the basis of its youngest contained detrital zircon population (Fyffe et al. 2009). The presence of sedimentary xenoliths within the Stanley Brook

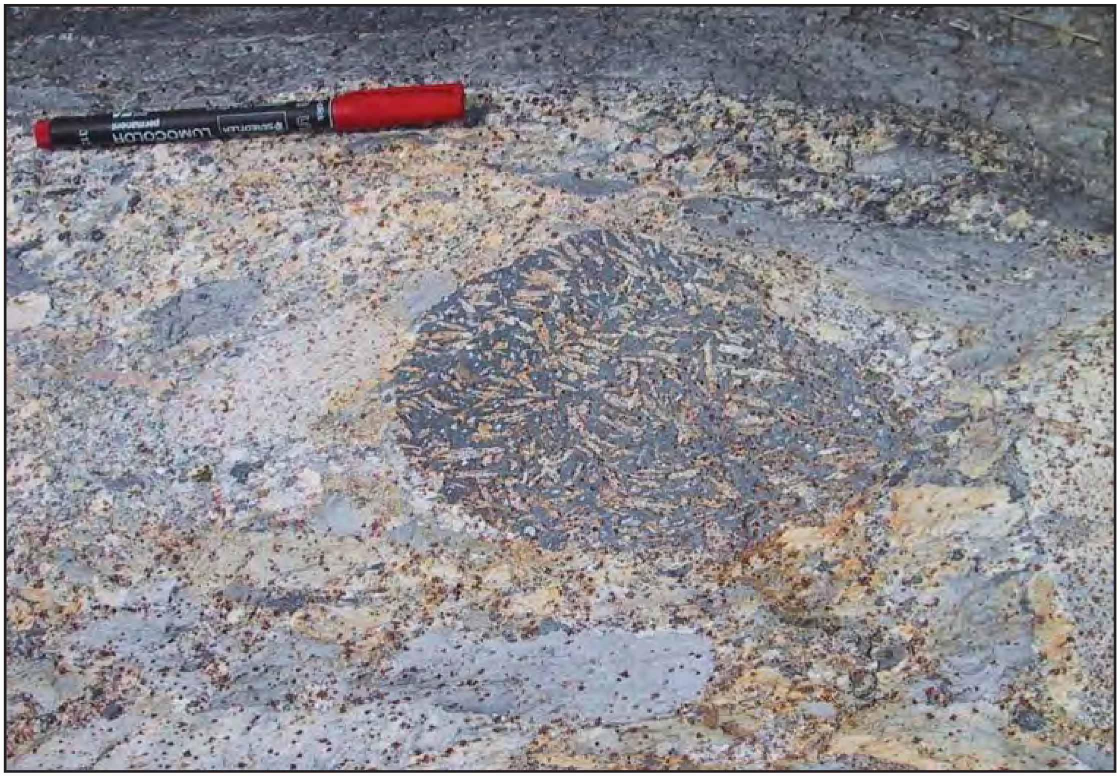


Figure 8. Clast of plagioclase-phyric mafic volcanic rock in conglomerate of the Great Duck Island Formation on Great Duck Island (photograph from Black 2005).

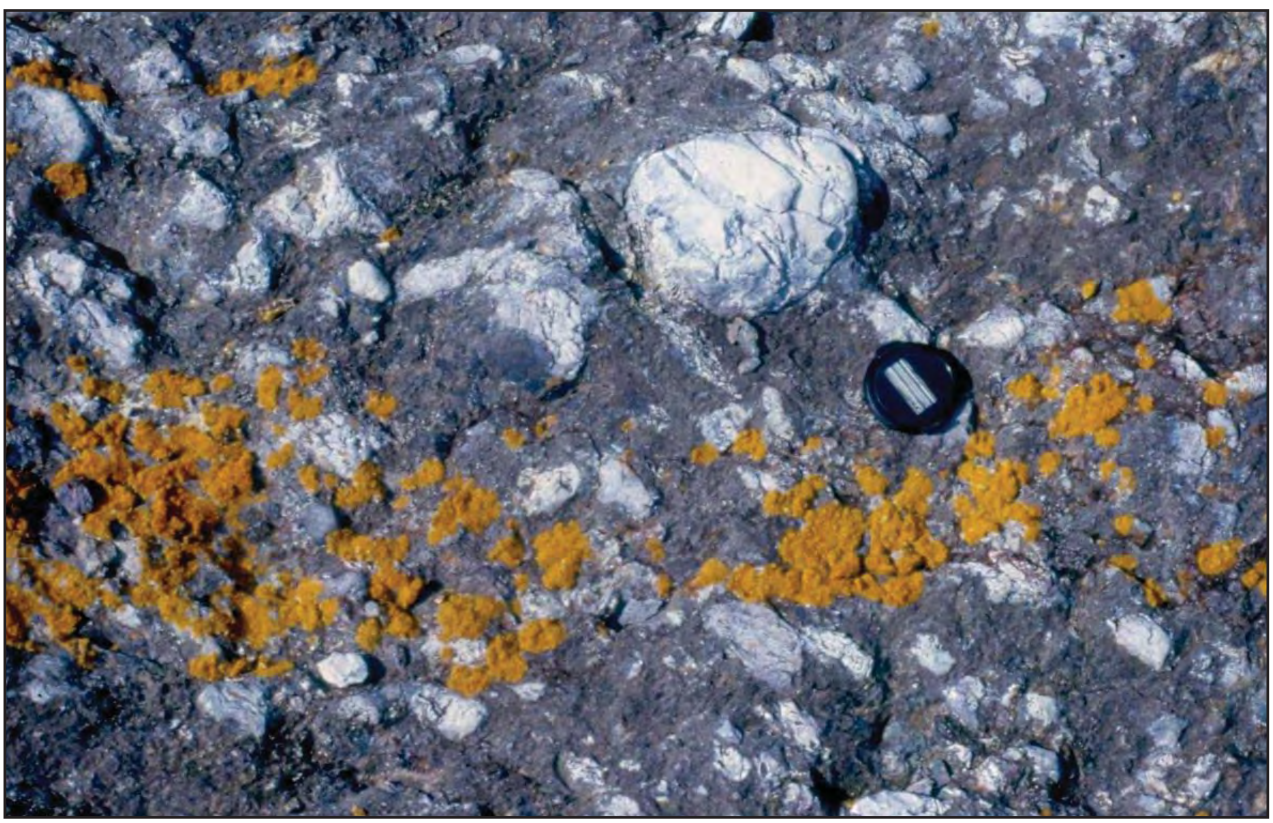


Figure 9. Clasts of quartzite in conglomerate of the Great Duck Island Formation at The Dock, Island of Grand Manan.

Granite (Fig. 12) indicates that the Flagg Cove Formation is no younger than 535 ± 2 Ma, the age of emplacement of this intrusion (see below). The maximum stratigraphic age of the Flagg Cove Formation is constrained to be no older than 574 ± 7 Ma on the basis of its youngest contained detrital zircon population (Fyffe et al. 2009). The age of the Flagg Cove Formation and Great Duck Island Formation, its near-shore lateral equivalent, is, therefore, restricted to between the latest Neoproterozoic and earliest Cambrian.

The Priest Cove Formation underlies much of the eastern part of Grand Manan from Grand Harbour in the south to Castalia in the north (Fig. 3). Interstratified greyish green, medium- to thick-bedded mafic lithic tuff and volcaniclastic sandstone that characterize this formation are best exposed in coastal sections at Phillips Point, Priest Cove, Ragged Point, Bancroft Point, and Castalia. Bedding in the volcaniclastic sandstone typically fines upward over 30 cm from a coarse-grained base to 3 cm of laminated, fine-grained sandstone at the top; grading indicates younging consistently to the north (Fig. 13).

Minor felsic crystal tuff is interbedded with mafic volcaniclastic sandstones on the Shore Road to Priest Cove. This felsic tuff has been dated by U/Pb on zircon as 539 ± 3 Ma (Black et al. 2004; Miller et al. 2007), suggesting a cogenetic relationship with the Stanley Brook Granite dated at 535 ± 2 Ma (see below). The contact between the Priest Cove and Flagg Cove formations is invariably faulted. However, the cogenetic relationship between the Priest Cove Formation and Stanley Brook Granite suggests that the Priest Cove Formation was deposited upon the Flagg Cove Formation, since the latter is intruded by the granite. This proposed stratigraphic relationship supports the interpretation that the mafic tuffs and volcaniclastic sandstones of the Priest Cove Formation represent a distal facies of the mafic flows and breccias of the Ross Island Formation, which are also known to be younger than the Grand Manan Group on the basis of contained granitic clasts (see below).

The Early Cambrian Priest Cove Formation of the Castalia Group is identical in age to volcanic rocks of the Simpsons Island Formation (539 ± 5 Ma) of the Belleisle Bay Group in the New River Terrane on the New Brunswick mainland. However, no older volcanic rocks of the ca. 550 Ma age group, common elsewhere in the New River Terrane, have been identified on the Island of Grand Manan.

The Ross Island Formation, which underlies the greater part of Ross and Whitehead islands off the southeastern coast of Grand Manan, comprises interstratified plagioclase-phyric mafic and intermediate flows and breccias intruded by numerous diabase dykes and dykelets. The flows are locally pillowed (Fig. 14) and interbedded with green laminated siltstone. Compositionally, these volcanic rocks range from calc-alkaline basalt to basaltic andesite and andesite (Table 1) (Hilyard 1992; Hewitt 1993; Hodgins 1994; Pe-Piper and Wolde 2000). They may be the proximal equivalents to the mafic tuffs and volcaniclastic sandstones of the Priest Cove formation (Stringer and Pajari 1981).

A mafic debris flow within the Ross Island Formation (Fig. 15), exposed along the western shore of Ross Island, contains subangular, cobble- to boulder-sized clasts of granite, granitic pegmatite, and micaceous quartzite. The granite clasts from the debris flow yielded K/Ar muscovite ages of 640 Ma and 590 Ma (Lowdon et al. 1963; Leech et al. 1963; Stringer and Pajari 1981).

Figure 10. Medium-bedded, quartzose sandstone and laminated silty shale of the Flagg Cove Formation in Flagg Cove south of the Ferry Terminal, Island of Grand Manan.

Figure 11. Tightly folded, thin-bedded, quartzose sandstone and shale of the Flagg Cove Formation just north of The Dock, Island of Grand Manan.

Figure 12. Laminated sandstone xenolith of the Flagg Cove Formation in Stanley Brook Granite at Flagg Cove south of the Ferry Terminal, Island of Grand Manan.

The exposed contacts between The Thoroughfare and Ross Island formations are faulted as seen on the northern tip of Ross Island and western tip of White Head Island (Fig. 3). However, the presence of quartzite and granite clasts within the volcanic rocks of the Ross Island Formation indicates that at least part of the Castalia Group was deposited on a substratum composed of sedimentary rocks similar to The Thoroughfare Formation and intrusive rocks similar to the Three Islands Granite.

The North Head Formation, which underlies North Head near the northern tip of the Island of Grand Manan, consists of massive mafic to intermediate volcanic flows and breccia (Fig. 16) similar to those of the Ross island Formation (Table 1). The steeply dipping Red Point Fault (see below) separates these deformed volcanic rocks from the essentially flat-lying Triassic basalt of the Dark Harbour Formation exposed to the west of Whale Cove. A Triassic dyke intrudes the North Head Formation at Sawpit Cove under the footbridge to Swallow Tail Point (Fig. 17).

The Long Pond Bay Formation, exposed along Long Pond Bay from Long Pond to Red Point along the southeastern coast of the Island of Grand Manan (Fig. 3), is a sequence of mafic volcanic, volcaniclastic, and clastic sedimentary rocks. A series of southwest-directed thrusts divides the sequence into a number of fault slices. A black argillite mélange (Fig. 18) separates a predominantly volcanic and volcaniclastic sequence in the southwest from a predominantly clastic sedimentary sequence farther to the northeast. The mafic volcanic rocks are hyaloclastic tuffs and breccias.

The mafic volcanic rocks are interstratified with a thin-bedded sequence of rhythmically interbedded greyish green laminated siltstone and fine-grained, grey sandstone (Fig. 19). The presence of these fine-grained, volcaniclastic sedimentary rocks suggests that the Long Pond Bay Formation was deposited in a deeper marine depositional environment than the coarse, reworked mafic tuffs of the Priest Cove Formation.

Northeast of the black argillite mélange, a 10-m thick unit of sedimentary breccia (Fig. 20) is interbedded locally with laminated clastic siltstone (Fig. 21). Angular fragments of laminated siltstone, ranging from 1 to 10 cm in length, set in the sandy matrix indicate that the conglomeratic breccias were deposited as debris flows that incorporated material ripped up from a silty substrate. Medium-bedded, grey feldspathic sandstone displays sedimentological features characteristic of deposition by turbidity currents (Fig. 22) is exposed about 500 m southwest of Long Pond. Beds in the sandstone typically grade upward from a coarse base, containing rip-up clasts of the underlying shale, through to medium-grained sandstone into a laminated shale interval at the top.

On Wood Island off the southeastern coast of Grand Manan, the Long Bay Pond Formation comprises a north-facing sequence of oxidized, coarsely amygdaloidal mafic (Fig. 23) and minor felsic flows interstratified with 50 m thick intervals of medium-bedded, greyish green volcaniclastic sandstone (Fig. 24) grading to laminated maroon mudstone. Red arkosic grits and silty red shale (Fig. 25) are locally interbedded with the mafic volcanic rocks suggesting deposition in a subaerial to very shallow marine environment. Xenocrystic zircons from a felsic volcanic rock provide a maximum age for the Wood Island section of ca. 588 Ma (Miller et al. 2007).

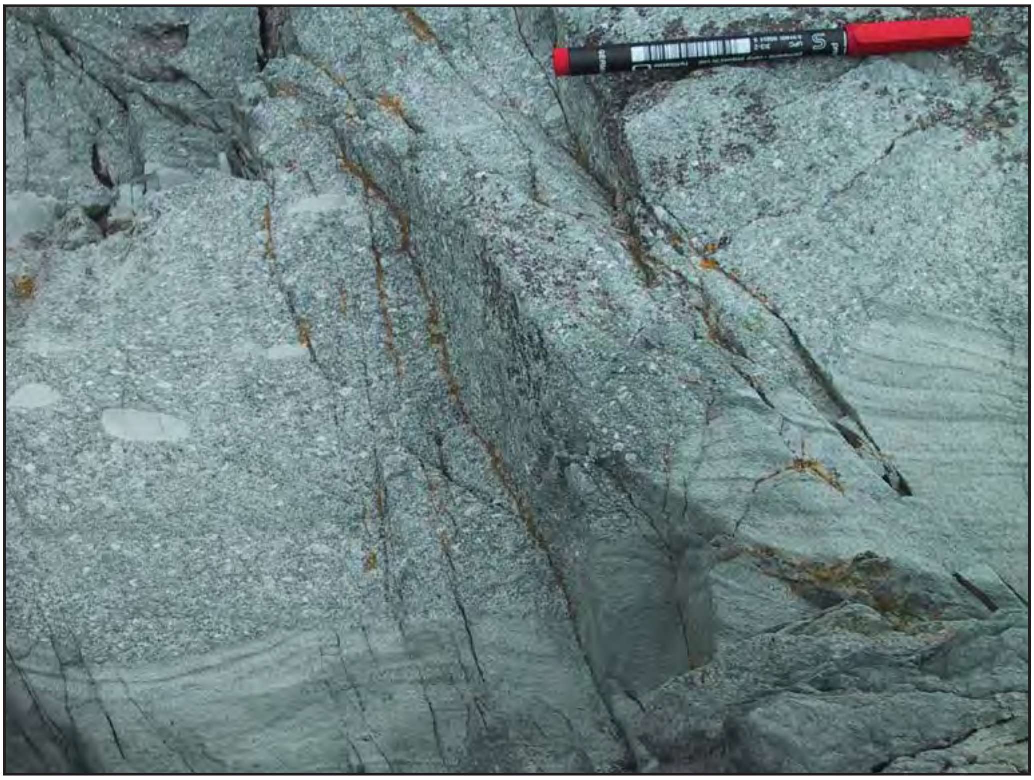


Figure 13. Laminated, fine-grained, volcaniclastic sandstone and overlying medium-bedded, coarse-grained, volcaniclastic sandstone of the Priest Cove Formation on southern end of Nantucket Island (photograph from Black 2005).

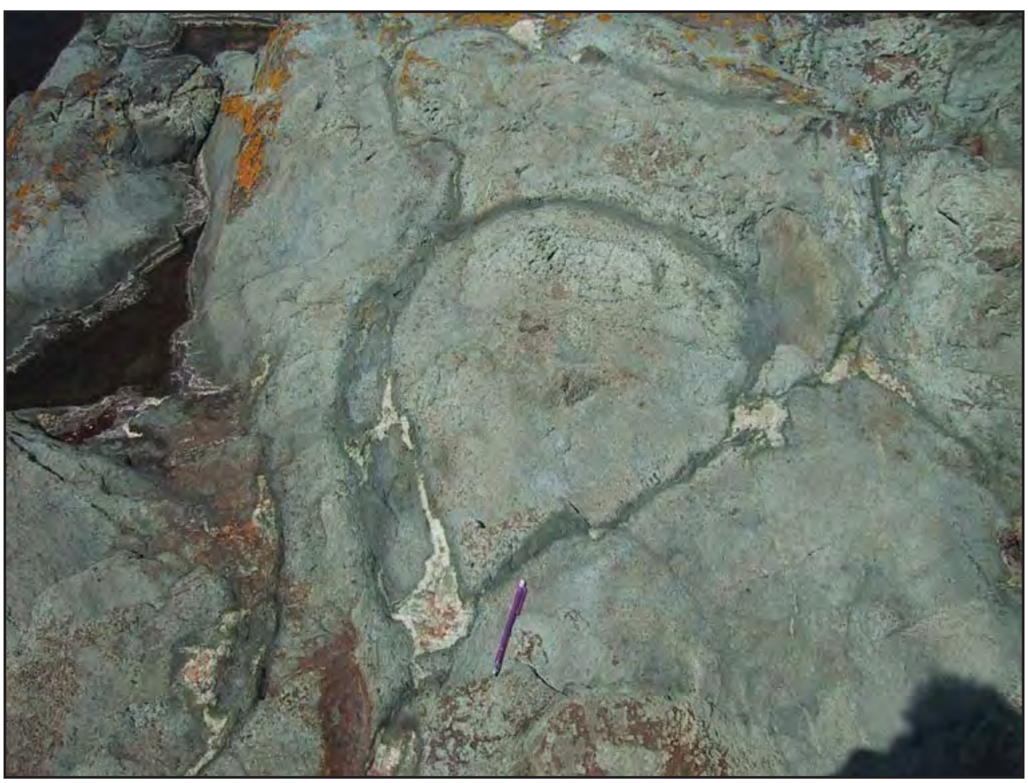


Figure 14. Pillow basalt of Ross Island Formation on White Head Island (photograph from Black 2005).

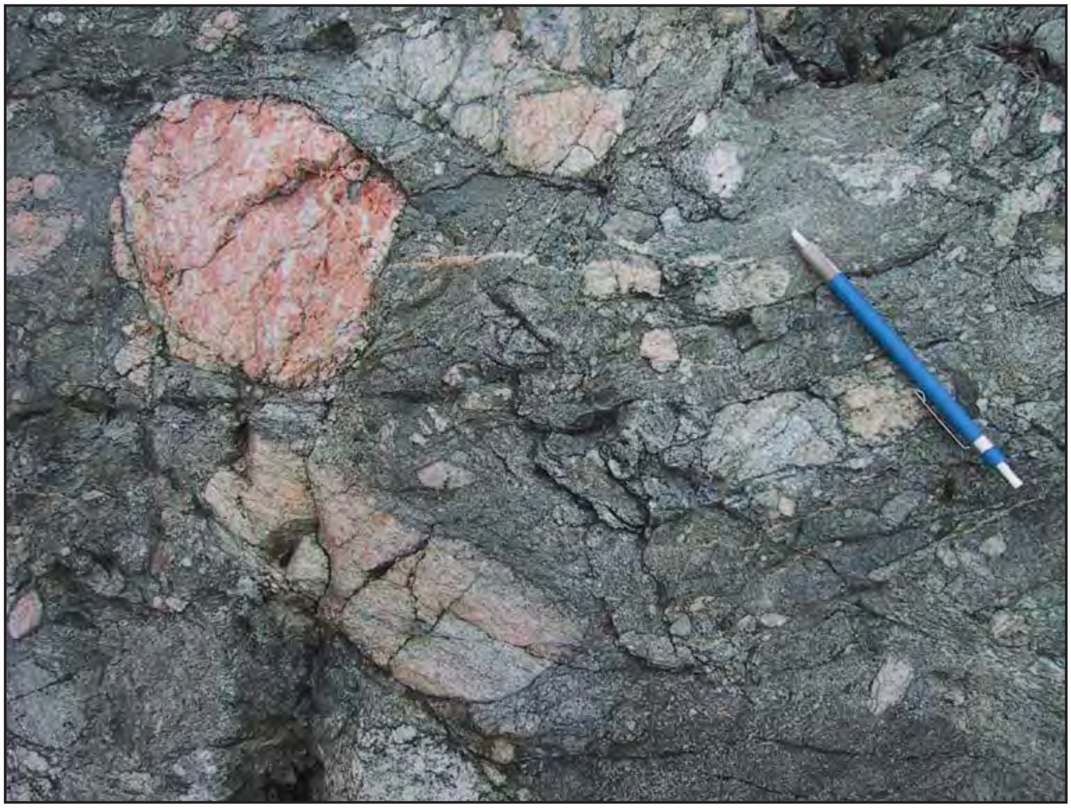


Figure 15. Mafic debris flow of Ross Island Formation on west side of Ross Island containing large clasts of granite and micaceous quartzite (photograph from Black 2005).

Figure 16. Mafic volcanic breccia of North Head Formation veined by quartz at Swallow Tail Head.

Figure 17. Triassic Sawpit Dyke intruding latest Neoproterozoic to earliest Cambrian mafic volcanic rocks of the North Head Formation at the Swallow Tail Head.

Figure 18. Volcanic block in argillite mélange of the Long Pond Bay Formation along Long Pond Bay, Island of Grand Manan.

Figure 19. Thin-bedded volcaniclastic sequence of rhythmically interstatified, laminated greyish green siltstone and fine-grained, grey sandstone of the Long Pond Bay Formation along Long Pond Bay, Island of Grand Manan.

Figure 20. Sedimentary breccia of the Long Pond Bay Formation along Long Pond Bay, Island of Grand Manan.

Figure 21. Thin-bedded, laminated siltstone of the Long Pond Bay Formation along Long Pond Bay, Island of Grand Manan.

Figure 22. Open fold in medium-bedded, feldspathic sandstone of the Long Pond Bay Formation along Long Pond Bay to the southwest of Long Pond, Island of Grand Manan.

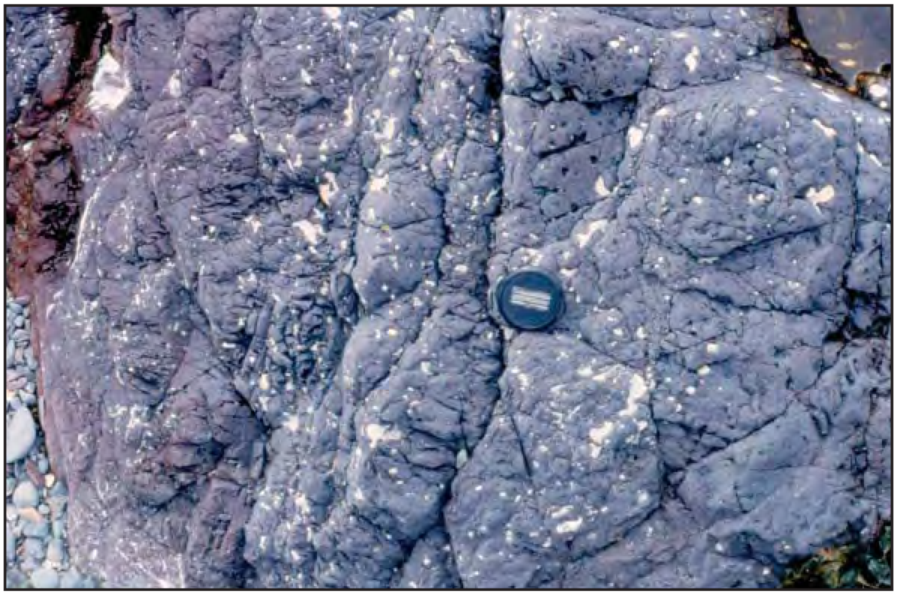


Figure 23. Amygdaloidal mafic flow of the Long Pond Bay Formation on Wood Island.

Figure 24. Medium-bedded, volcaniclastic sandstone of the Long Pond Bay Formation on Wood Island. Note the laminations at the top of beds.

Figure 25. Arkosic sandstone of the Long Pond Bay Formation on Wood Island. Note the pink rhyolite pebbles.

Table 1. Chemical analyses of Neoproterozoic to Cambrian volcanic rocks, Island of Grand Manan, New Brunswick.

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Oxides													
SiO_2	45.15	45.93	52.25	55.82	57.56	57.77	58.47	61.11	61.41	65.67	66.23	47.54	55.70
TiO_2	1.11	1.85	1.45	1.24	1.12	1.06	1.14	1.11	1.14	0.74	0.75	1.11	1.48
Al_2O_3	18.16	17.91	15.44	16.12	15.90	14.45	14.23	14.78	14.33	14.90	15.18	14.90	15.70
Fe_2O_3	13.35	10.81	9.84	8.04	8.43	8.54	8.57	7.64	8.21	5.47	6.32	11.40	9.08
MnO	0.15	0.19	0.18	0.14	0.12	0.12	0.16	0.11	0.10	0.08	0.04		
MgO	2.11	7.30	7.00	4.92	4.81	1.98	5.21	3.40	4.83	0.87	0.69	10.20	4.46
CaO	17.44	4.92	5.94	5.50	5.19	12.17	4.09	4.68	3.33	1.71	0.50	12.60	8.74
Na_2O	0.39	1.25	3.19	3.71	4.40	1.81	3.86	4.21	2.63	2.36	2.75	1.78	4.24
K_2O	0.20	5.32	0.94	1.73	0.48	0.17	0.48	1.95	1.32	6.08	5.63	0.49	2.11
P_2O_5	0.45	0.78	0.52	0.41	0.25	0.41	0.53	0.39	0.11	0.16	0.15		
LOI	2.70	3.80	2.90	2.20	2.20	1.40	2.30	1.30	3.60	2.60	1.60		
Total	101.21	100.06	99.65	99.83	100.46	99.88	99.04	100.68	101.01	100.64	99.84		
Traces													
Ba	61.41	65.67	448	638	135	53	176	680	259	730	618	111	137
Rb	20	90	19	41	42	14	11	10	57	219	210		
Sr	1350	159	309	348	333	969	177	388	96	54	38	400	294
Y	19	43	31	36	33	24	33	38	41	58	64	21	60
Zr	238	269	165	258	210	216	182	215	185	491	517	121	207
Nb	11	19	12	14	12	11	13	11	11	19	19		
Th	4	5	4	6	4	4	2	7	6	13	14		
Pb	29	3	4	8	7	18	5	10	7	5	8		
Ga	17	14	13	17	17	16	17	18	18	20	21		
Zn	39	145	131	91	68	27	103	78	84	60	64	97	121
Cu	36	11	11	6	6	21	46	9	6	16	3	0	36
Ni	20	47	77	28	31	30	43	13	4	4	2	81	42
V	296	228	235	172	185	189	190	138	146	45	43	228	130
Cr	128	218	223	142	175	119	178	125	17	7	8	355	85
Co		40	35	30		37	40	31	31		14	57	30
Sc		36	28	24	15	23	23	22	28		11	46	28
Hf		6.5	3.9	5.8		4.2	4.2	5.3	4.9		13		
U		1.01	1.00	0.81	1.00	0.54	1.28	1.33	2.30	6	3.5		
REEs													
La		48	22	32	26	30	33	28	24		50	10	25
Ce		106	52	67		65	71	61	53		107	21	56
Nd		55	31	33	30	31	37	31	29		52	13	31
Sm		10.8	6.5	7.1		6.4	6.9	6.1	6.4		10.5	3.7	7.3
Eu		2.5	2.1	2.0		1.8	1.8	1.7	1.2		1.91	1.1	
Tb		1.6	1.1	1.1		0.9	1.1	1.0	1.2		1.94		
Yb		4.6	3.1	3.5		4.1	3.0	2.8	3.9		6.2	0.9	1.3
Lu		0.66	0.45	0.50		0.40	0.44	0.42	0.56		0.88		

Notes:

Samples 1–8 Ross Island Formation (Pe-Piper and Wolde 2000)
Samples 9–11 Ingalls Head Formation (Pe-Piper and Wolde 2000)
Samples 12–13 North Head Formation (Hewitt 1993)

Oxides in weight per cent; traces and REEs in parts per million

Felsic Plutonic Rocks

The Stanley Brook Granite is exposed for a distance of about 400 m along the shore of Flagg Cove to the south of Stanley Brook (Fig. 12). The granite is light pink, foliated, medium-grained, and along its northern boundary contains elongated xenoliths of greyish green siltstone from a few centimetres to a few metres in length (Fyffe et al. 2011c). The xenoliths are commonly cross-cut by folded and brecciated veins of pink granite. A zone of phyllonitic granite about 2 m wide, trending 175° and dipping 80° W, marks the sheared northern contact with sedimentary rocks of the Flagg Cove Formation. Some of the siltstone xenoliths within the granite contain thin beds of quartzose sandstone identical to those in the adjacent Flagg Cove Formation, suggesting that displacement along the contact is not significant.

The southern portion of the Stanley Brook Granite consists of a mixture of intermingled pink granite veins, and hybridized inclusions of greyish green, fine medium-grained, plagioclase-phyric diorite. The diorite is speckled with pyrite cubes, and contains abundant quartz crystals in places where it has been largely assimilated by the granite. A northwesterly trending brittle fault, exposed in the cliff face along the shore, marks the southern limit of Stanley Brook Granite. The southeastern projection of the brittle fault truncates a three-metre wide shear zone exposed in the foreshore a short distance to the north. The shear zone, which trends at 30º and dips 70º northwest, separates phyllonitic hydrid rocks containing small (1 cm in length) rounded, cataclastic fragments of granite from adjacent sedimentary rocks of the Flagg Cove Formation to the southeast.

The age of 535 ± 2 Ma of the Stanley Brook Granite and the age of 547 ±1 Ma of the High Duck Island dyke that intrudes maroon siltstone of the Ingalls Head Formation exposed on the shore north of Castalia (Black et al. 2004) on the Island of Grand Manan, and the 542 ± 1 Ma age of the Machias Seal Island Monzodiorite to the southwest of Grand Manan (Barr et al. 2010), all overlap with the 548 ± 2 to 528 ± 3 Ma age range of the Neoproterozoic to Early Cambrian plutonic rocks of the Brookville Terrane on the New Brunswick mainland (White et al. 2002).

The Three Islands Granite underlies Kent, Hay, and Sheep islands (Three Islands) off the southern coast of the Island of Grand Manan. This medium-grained, dark pinkish red, equigranular granite is locally sheared and transected by thick quartz veins and diabase dykes, and contains large blocks of Kent Island marble. Zircons from the granite yield an age of 611 ± 2 Ma (Barr et al. 2003a), similar to the age of volcanic rocks of the Ingalls Head Formation (618 ± 3 Ma) on the Island of Grand Manan (Barr et al. 2003a; Miller et al. 2007). Neoproterozoic granitic plutons (629 ± 1 to 622 ± 2 Ma) in the New River Terrane on the mainland of New Brunswick overlap within limits of error with the age of the Ingalls Head volcanic rocks (Johnson and Barr 2004; Bartsch and Barr 2005). The Kent Island marble of the Grand Manan Group closely resemble that of the Green Head Group of Brookville Terrane.

Mafic Plutonic Rocks

The Fish Head Gabbro, which is exposed on Fish Head at the northern tip of North Head on the Island of Grand Manan (Fig. 3), is a dark grey, medium-grained, massive gabbro, locally veined by gabbroic pegmatite. The pluton is tentatively assigned an Early Cambrian age on the basis of its intrusive relationship with mafic volcanic rocks of the supposedly Late Neoproterozoic to Early Cambrian North Head Formation of the Castalia Group.

The Rockweed Pond Gabbro is exposed on Ross Island just northeast of Rockweed Pond and on Cheney Island off the eastern coast of the Island of Grand Manan (Fig. 3). The pluton is composed of dark grey, medium-grained gabbro, locally veined by greyish pink, foliated, medium-grained granite. It is assigned an Early Cambrian age on the basis of its intrusive relationship with mafic volcanic rocks of the supposedly Late Neoproterozoic to Early Cambrian Ross Island Formation. Diabase dykes intruding volcanic rocks of the Neoproterozoic Ingalls Head Formation on Ingalls Head on the Island of Grand Manan and injecting the supposedly Mesoproterozoic quartzites of The Thoroughfare Formation on the eastern shore of Ross Island near Edmunds Rock (Hodgins 1994) may be contemporaneous with the gabbro.

The Outer Wood Island Gabbro underlies Outer Wood Island off the southeastern coast of the Island of Grand Manan (Fig. 3). The pluton is composed of dark grey, medium-grained, massive gabbro, locally veined by gabbroic pegmatite. The gabbro is tentatively assigned an Early Cambrian age on the basis of its similarity to the Rockweed Pond Gabbro.

Structural Geology

The following summary of the structural features in the pre-Mesozoic rocks of Grand Manan is taken largely from Stringer and Pajari (1981). Bedding in the sedimentary rocks and of primary layering in the volcanic rocks show considerable variation in strike and dip due to polyphase deformation. Five phases of deformation (D_1 to D_5) have been established on the basis of overprinting relationships and characteristic style and orientation of minor structures formed during each phase. Some or possibly all of this penetrative deformation post-dates emplacement of the highly sheared, Early Cambrian Stanley Brook Granite, the youngest unit recognized on the Island of Grand Manan.

The S_1 foliation formed during D_1 is defined by an alignment of fine-grained, mainly sericitic micaceous minerals and elongate quartz grains which constitutes a penetrative fabric subparallel to bedding in sedimentary rocks of The Thoroughfare and Flagg Cove formations. A spaced platy cleavage subparallel to the primary layering in volcanic rocks of the Ingalls Head Formation and locally in those of the Priest Cove Formation is interpreted as S_1 foliation. Volcaniclastic fragments oriented parallel to the S_1 foliation appear flattened and elongated within S_1, forming a lineation (L_1) that trends predominantly northwest within the composite S_1/S_0 surface. F_1 minor folds have not been observed.

The S_2 crenulation cleavage is defined by microfolds of the composite S_1/S_0 foliation. The S_2 cleavage generally trends to the northwest and dips moderately toward the northeast or southwest, varying locally due to later folding. F_2 minor folds are tight, asymmetrical, and mostly plunge steeply to the southeast. The S_3 crenulation cleavage strikes northwest and is mainly subvertical. F_3 folds are upright, open to tight, and symmetrical or slightly asymmetrical, and they deform F_2 folds in the vicinity of The Thoroughfare and on the south side of Flagg Cove. The F_3 folds mostly plunge gently to the southeast or northwest.

The S_4 cleavage is defined by spaced (1–30 mm) partings that are particularly well developed in thick-bedded volcaniclastic sandstones of the Priest Cove Formation. The cleavage dips gently to moderately westward and is associated with open to tight asymmetrical F_4 folds that persistently verge eastward. The regular orientation of S_4 cleavage suggests that the variation in F_4 fold plunge is largely due to pre-D_4 variation in dip and strike of the earlier planar structures. The S_5 cleavage is defined by spaced (5 to 50 mm) partings that are developed in only a few localities such as in the volcaniclastic rocks at Woodwards Cove. The S_5 cleavage is subvertical with a west to northwest strike.

Chloritoid crystals 0.1-0.5 mm in length are locally abundant in pelitic and graphitic sedimentary rocks of The Thoroughfare Formation. The chloritoid crystals overprint $S_{2,}$ S_3 and S_4 cleavage films but their time relationship with respect to the D_5 deformation has not been observed. The rosettes of chloritoid suggest that the mineral crystallized under static conditions, which may have succeeded D_5 deformation.

Westward-directed thrusts that place the Ingalls Head and The Thoroughfare formations of Grand Manan Group over the Long Pond Bay and Priest Cove formations of the Castalia Group can be observed on the west side of The Thoroughfare (Fig. 3). Southwestward-directed thrusts and associated mélange within the mafic volcanic rocks of the Long Pond Bay Formation are likely related to this same period of deformation (Fyffe et al. 2011a). The S_2 cleavage appears to be shallower and more penetrative near the thrust front.

The thrusting events on the Island of Grand Manan may be related to emplacement of the Avalonian Caledonia Terrane over the Ganderian Brookville and New River terranes on the New Brunswick mainland during the Acadian Orogeny (cf. Keen et al. 1991). Similar thrusts are present along the Bay of Fundy coast on the mainland of New Brunswick, the Kenebecasis-Pocologan Fault being a prime example (Fig. 1, 2). Movement on this fault is known to have been active both during the Late Silurian–Early Devonian and the Carboniferous (Rast and Grant 1973; Nance 1985; Nance and Warner 1986; Park et al. 1994). The thrusting events on the mainland and on Grand Manan may have been initiated during delamination of the down-going Avalonian plate (Caledonia Terrane) beneath the Coastal Arc following closure of the Silurian Kingston and Mascarene basins (Fyffe et al. 1999; White et al. 2006; van Staal et al. 2009, 2012). North-northwesterly-trending strike-slip faults concentrated in the vicinity of North Head may represent the continuation of the Oak Bay Fault system on the mainland.

Triassic Geology of the Island of Grand Manan

The western side of the Island of Grand Manan exposes sedimentary and basaltic strata of the Grand Manan Basin, a small Early Mesozoic rift basin separated from the much larger Fundy Basin by the White Head horst, which is an uplifted section of Precambrian to Early Cambrian basement rocks exposed on the eastern part of Grand Manan and its archipelago of smaller islands (Fig. 3). The Red Point Fault (Fig. 26), which divides Grand Manan, defines the eastern border of the Grand Manan Basin (Fig. 27), whereas the Grand Manan Fault defines the western edge of the Fundy Basin in the Bay of Fundy immediately east of the archipelago (Fig. 28).

Figure 26. Basin border fault at Red Point, looking north. Late Triassic columnar basalt of the Southwest Head Member of the Dark Harbour Basalt (to the left) has moved downward against latest Neoproterozoic to earliest Cambrian, thin-bedded, volcaniclastic siltstone of the Long Pond Bay Formation (to the right).

Late Triassic basalt on Grand Manan and small sections of underlying clastic strata are closely correlated with lithologies of the Fundy Group across the Bay of Fundy and exposed in southwestern coastal Nova Scotia (Greenough 1995; Kontak 2008; Wade et al. 1996). Lithologies and structures in both areas reveal the sequence of events near the Triassic–Jurassic boundary in this region (McHone 2011; Wade et al. 1996; Olsen 1997). Interpretations by McHone (2011) for Mesozoic features in New Brunswick include likely connections between source dykes and the massive flood basalts, the development and emplacement of volcanic members in a massive lava (magma) lake, and subsequently faulted borders of strata that were separated into their modern geographic patterns by uplift and erosion. The region also yields evidence concerning the great end-Triassic extinction event (Olsen et al. 2005; Deenen et al. 2010; Blackburn et al. 2013).

Previous Work

The Mesozoic rocks of Grand Manan received only minor attention during the 19th and 20th centuries. Descriptions by Gesner (1839) and Bailey (1872) were reasonably good for the times,

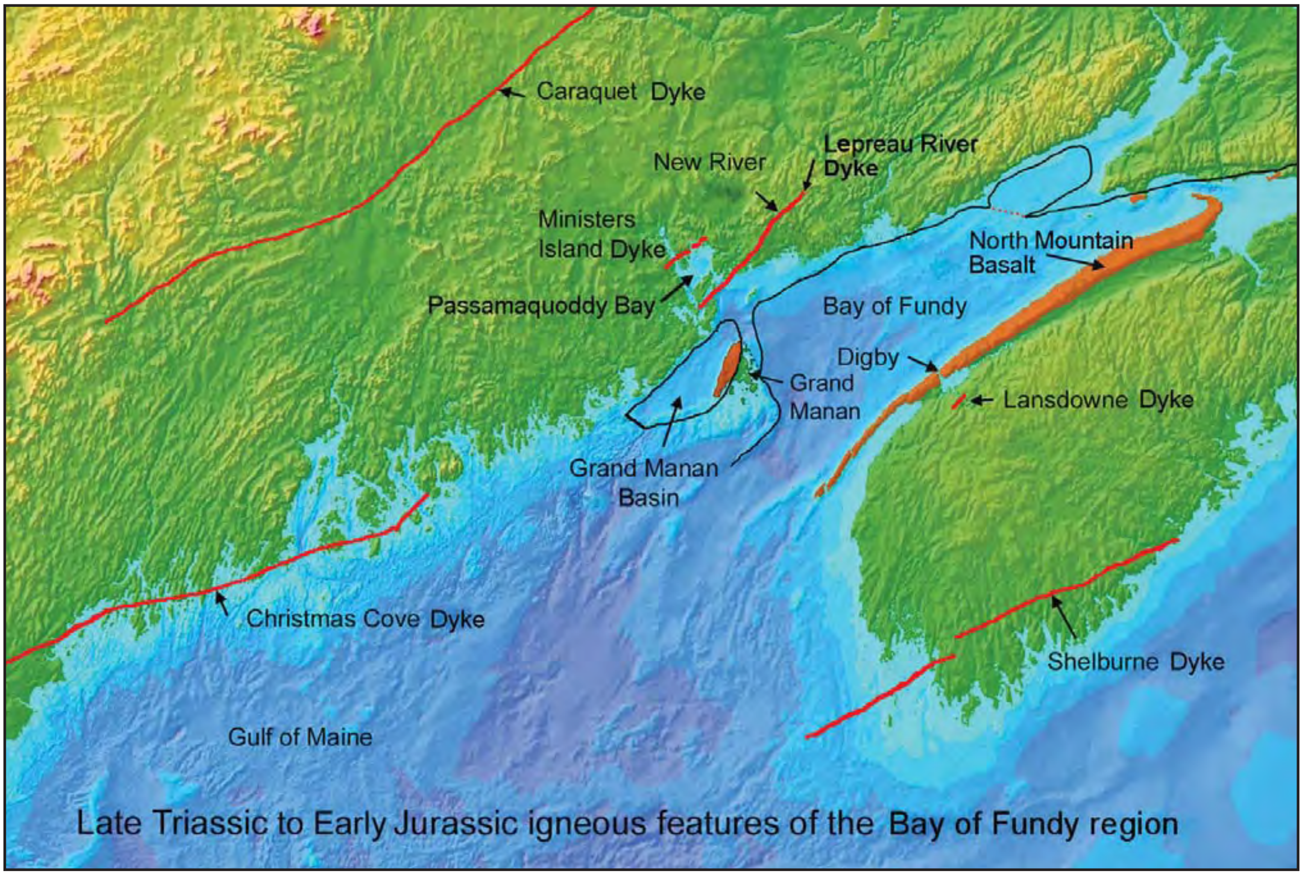


Figure 27. Outlines of Early Mesozoic basins and locations of large tholeiitic dykes and basalt in the Bay of Fundy region.

including the recognition of the differences between the east and west sides of Grand Manan, the Triassic (New Red Sandstone) age of the basalts and underlying sedimentary rocks, and similarities with formations farther north around the Bay of Fundy. Alcock (1948) added some detail for the eastern basement rocks and also located the red conglomeratic sandstone at Miller Pond Road, which he mapped as beneath the basalt. In other areas of the Bay of Fundy, seismic surveys conducted by oil and gas exploration companies were used by Wade et al. (1996) to produce major advances in our understanding of the Mesozoic stratigraphy and structures of the region (Fig. 27).

Students and faculty from the Geology Department at University of New Brunswick spent several seasons in the 1960s and 70s examining Grand Manan geology, leading to some master's theses (e.g., Gunter 1967) and a few publications (e.g., Trembath 1973). Under the leadership of George Pajari, a UNB team constructed an exhibit of the island geology at the Grand Manan Museum, which emphasized the Mesozoic section. This exhibit was enlarged and updated in 2011.

McHone (2011) has mapped the Triassic basalt in more detail and with a simpler arrangement of members in vertical sequence (Fig. 28). Large areas are still questionable because of difficult access and lack of outcrops over much of the interior, but the updates have been added to the provincial map of Grand Manan (Fyffe et al. 2011a). Earlier field guides to the Mesozoic geology of Grand Manan were produced for a New England Intercollegiate Geological Conference (McHone 2001), and as a local geological guide for the general public (McHone and McHone 2012).

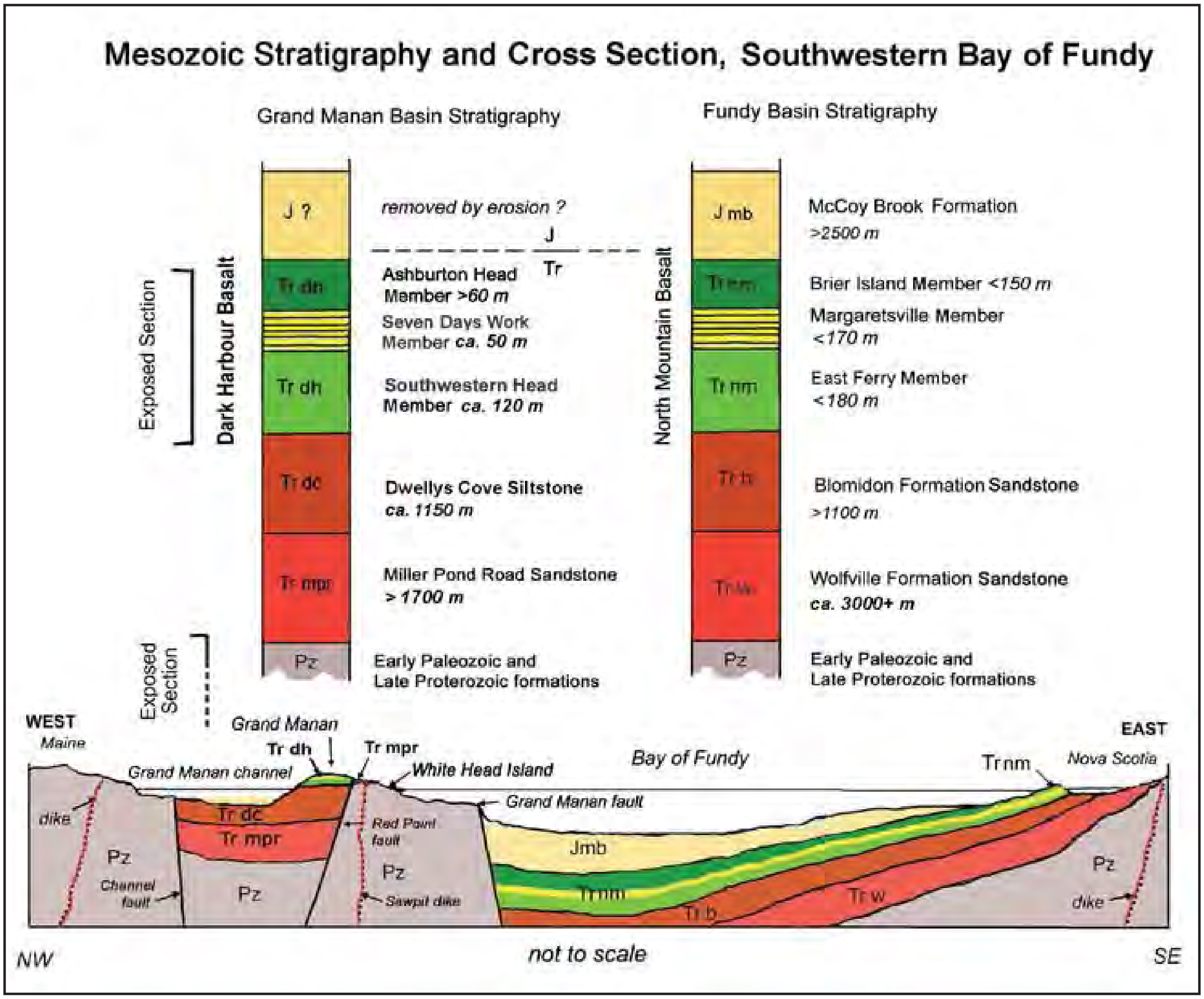


Figure 28. Idealized cross-section and correlated stratigraphic columns of the Grand Manan Basin and southern Fundy Basin between Maine (U.S.A.) and Nova Scotia (Canada), after Wade et al. (1996) and McHone (2011).

Mesozoic Basins

The Bay of Fundy includes a very large (~ 22,500 km^2) region of Early Mesozoic rift basins (Fig. 27), which are the northernmost examples of numerous basins along eastern North America (Olsen 1997). These basins host lava flows of quartz tholeiite with initial ages near the end of Triassic followed by Early Jurassic basalts in basins to the south (Jourdan et al. 2009). Three members of this early basalt are found in the Grand Manan, Fundy, and Minas basins, along with fluvial and lacustrine sandstones beneath and above the basalt. Mesozoic strata are better exposed in the much larger adjacent Fundy Basin and include two Late Triassic sandstone formations, the same end-Triassic tholeiitic basalt, and a partly carbonate to mainly clastic Early Jurassic sandstone formation (Olsen 1997). Thicknesses vary but reach a maximum in the south-central area of about 9 km (Wade et al. 1996). These formations are closely correlated among the regional basins and are referred to as the Fundy Group.

The Grand Manan Basin (McHone 2011) is a small Early Mesozoic rift basin with maximum dimensions around 30 km wide by 70 km long (approximately 1300 km^2) in the marine Grand Manan channel, with its western margin about 1 km or less offshore and parallel to the easternmost coast of Maine (Fig. 29). The international boundary between Canada and the United States extends through the centre of the channel and basin, but the border remains unresolved around North Rock and Machias Seal Island a few kilometres to the south of the basin.

The western basin margin is well defined by the Murr Escarpment, a straight and steep bathymetric slope close to the Maine coast that apparently marks a high-angle Mesozoic border fault (Barnhardt et al. 1996; Dickson et al. 1994). The eastern basin border is located by the Red Point Fault on Grand Manan (Fig. 3), which continues along a sharp break in the bathymetric topography to the southwest. The southwestern and northeastern ends of the basin are not accurately defined but are limited by bathymetric relief to the southwest, and by a seismic line across the Owen bathymetric basin south of The Wolves islands (Fig. 29) that shows no Mesozoic strata west of the Fundy Basin border fault (Wade et al. 1996; Wolczanski et al. 2007). Seismic survey lines reported by Tagg and Uchupi (1964) and Dickson et al. (1994) crossed the southwestern end of the Grand Manan Basin and indicate Mesozoic strata, but little about the basement and border structures.

Barnhardt et al. (1996) and Dickson et al. (1994) show that the Grand Manan Basin has a remarkably level and low-relief bathymetric depth around 70 m to 90 m (Fig. 29). The basalt flows and sedimentary strata on Grand Manan are also generally within a few degrees of horizontal, but with limited areas of wide gentle folds and a few normal faults. The subhorizontal strata are an exception to the general description of Early Mesozoic rift basins in eastern North America, which tend to be half-grabens with strata that dip toward one major border fault (Olsen 1997). The indication for the Grand Manan Basin is that its western and eastern border faults have similar vertical displacements, perhaps moving simultaneously.

Late Triassic to Early Jurassic sedimentary and volcanic formations of the Fundy Basin (Fig. 27) are well exposed along the western shorelines of Nova Scotia (Greenough 1995; Olsen 1997; Kontak 2008) and can be studied from seismic reflection surveys under the marine waters for much of the Bay of Fundy (Wade et al. 1996). Up to 8000 m of clastic sediments and 1000 m of basalt fill the south-central Fundy Basin, thinning to less than half that eastward into Nova Scotia (Fig. 28). In western Nova Scotia the Fundy Group strata generally dip around 10° to 15° NW, apparently due to normal faulting in the western part of the basin as well as subsidence toward south-central areas (Wade et al. 1996). In contrast, the sedimentary strata and lower basalt flows on Grand Manan are generally within 5° of horizontal except near faults, and with broad synclines and monoclines across the island in the upper basalt members.

The Fundy Group on the Island of Grand Manan

The nearest information for formations that are present offshore in the Grand Manan Basin is from the Mobil Gulf Chinampas N-37 deep exploration well drilled east of The Wolves, within the western Fundy Basin north of Grand Manan (Fig. 29). Formation thicknesses as summarized by Wade et al. (1996) are from top to bottom: 357 m of McCoy Brook Shale and siltstone; 333 m of

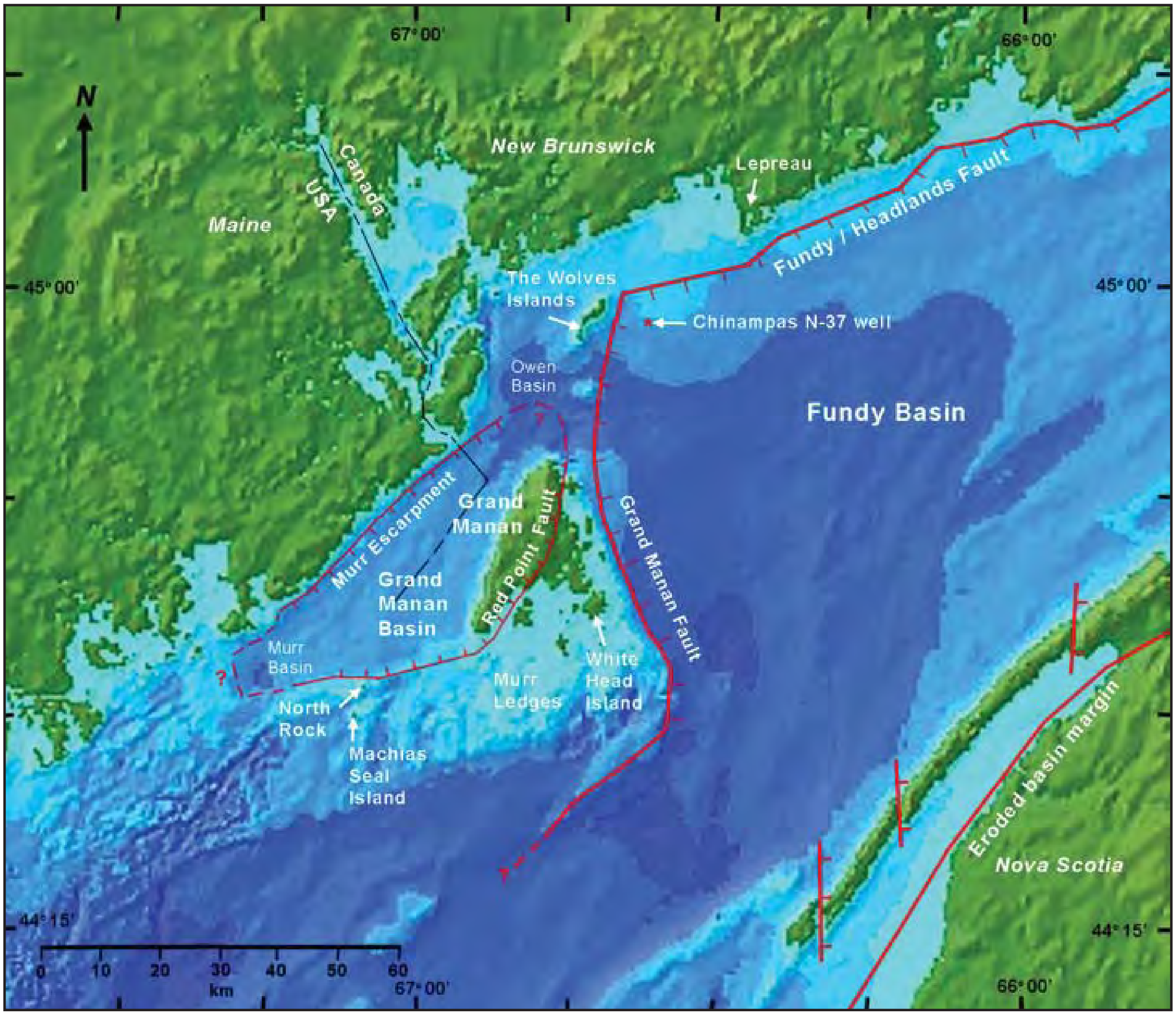


Figure 29. Bathymetry of the Grand Manan Basin area (blue) and topography of surrounding land areas (green). Dark blue areas indicate water depths exceeding 125 m. The relief base map is by Roworth and Signall (1998) with structural borders in red after Wade et al. (1996) and (McHone 2011). Line hachures indicate downdip offset directions on normal faults.

North Mountain Basalt; 1157 m of Blomidon Sandstone; and 1718 + m of Wolfville Sandstone (not completely penetrated). About 260-280 m of basalt are present at Grand Manan, but the top of the basalt, and any strata formerly above it, are apparently removed by erosion (Fig. 28). Formation thicknesses vary greatly across the Fundy Basin and the Chinampas well log can only be used for a rough estimate for the Grand Manan Basin. The petrography of basalt chips sampled by the well was described by Papezik and Greenough (1987).

The Fundy Group on the Island of Grand Manan includes from bottom to top: fluvial sandstone of the Miller Pond Road Formation, interpreted as a basal unit; fine-grained lacustrine mudstone and red sandstone of the Dwellys Cove Formation that underlie the basalt; and three volcanic members of the Dark Harbour Basalt (Fig. 28) (McHone 2011). The most recent map of bedrock geology of Grand Manan is by Fyffe et al (2011a).

Miller Pond Road Formation. Alcock (1948) noted the presence of “minor amounts of reddish and brownish sandstone and conglomerate” a few km to the southwest of Grand Harbour, which he mapped beneath the basalt along the western side of the Red Point Fault (Fig. 3). Alcock apparently did not see the distinctly different siltstone beneath basalt along the western shoreline (Fig. 3). Wade and Jansa (1994, p. 213) mention that they looked for, but did not find Alcock’s eastern sandstone. McHone (2011) found exposures along a bank on the southeastern side of an abandoned gravel quarry off Miller Pond Road, and within the area where it was originally mapped by Alcock (1948), but it is apparent that the sandstone is not beneath basalt west of the fault, which invites a new interpretation.

The medium-to coarse-grained, purplish red arkosic sandstone contains up to 10% feldspar grains, a trace of clay in the matrix, and is weakly cemented by iron oxide and calcite. Bedding is difficult to discern but appears to dip about 5° to 10° NE. The sandstone at the northern end of the bank lacks significant foreign rock fragments, but a few metres toward the south it contains scattered clasts of greyish green to rusty phyllitic volcaniclastic siltstone similar to the major lithology of the Long Pond Bay Formation at Red Point (Fig. 3). The clasts are angular and range around 0.2 cm to 4 cm in length. This phyllite appears to be the only clast lithology present in the Miller Pond Road sandstone.

Outcrops in the bank about 10 m to the southwest are downdip, and thus a metre or so stratigraphically below the level of the outcrop of conglomeratic sandstone. Here the sandstone grades into a mass of angular pieces of the same phyllite, becoming the matrix of clast-supported breccia or paleoregolith (Fig. 30). The angular fragments preserve a fabric or preferred orientation that might represent original cleavage in the bedrock, which appears to be dipping toward the north more steeply than the sandstone bedding. This field evidence indicates that the sandstone was deposited upon and grades into the top of the Long Pond Bay Formation, although solid bedrock of this basement rock is not locally exposed. Modern surface exposures of Long Pond Bay argillite are observed at Red Point to be brecciated into angular gravel identical to the clasts, apparently a function of rock cleavage and fracture patterns. The exact appearance of the basal unconformity at this location is obscured by vegetation and the intermixing of the formations in a paleoregolith.

The Miller Pond Road conglomeratic sandstone is very similar to a section of fluvial arkose in the Lepreau Formation near Maces Bay (Fig. 2), on the mainland coast north of Grand Manan (Wade et al. 1996). The Lepreau Formation is heterogeneous and includes much coarser conglomerates with a variety of clast lithologies (Nadon and Middleton 1984), whereas the Miller Pond Road sandstone has only small angular clasts of the underlying phyllite (although the exposure is very limited). The Lepreau sandstone also appears to be more strongly cemented. There as here, the Lepreau Formation represents the base of the stratigraphic section of the Fundy Group, but rather than Triassic, a Late Permian age is proposed (Olsen 1997; MacNaughton and Pickerill 2010). These early clastic deposits are in the Bay of Fundy region but not within the modern basins, although they are assigned to the first lithotectonic division (Unit TS1) of the Fundy Group (Olsen and Et-Touhami 2008).

Columnar Dark Harbour Basalt crops out in the hillside about 80 m to the northwest, just outside the level grounds of the gravel quarry. The Red Point Fault apparently runs along the base of this

Figure 30. Clast-supported conglomeratic sandstone of the Miller Pond Road Formation. The diameter of the coin is 23 mm.

fault-line scarp (Fig. 3), and the sandstone is east of the fault and not beneath basalt as shown by Alcock (1948). The sandstone does not resemble a typical basin margin alluvial conglomerates or fanglomerate, which normally contain a mix of rounded clasts of durable lithologies derived from adjacent highlands. The exposure at Miller Pond Road is interpreted to be a remnant of the base of Permian–Triassic basin strata that have been eroded from the White Head horst between the Grand Manan and Fundy basins (Fig. 28). It presents important implications about how the basins developed.

The Dwellys Cove Formation is exposed for 16 kms along the shoreline north and south of Dark Harbour, as pale maroon to light grey siltstone and shale in long and low outcrop intervals beneath and in contact with overlying basalt (Fig. 31). These sedimentary rocks were correlated with the Late Triassic Blomidon Formation of the northern Fundy Basin (Wade and Jansa 1994), also referred to as ‘Annapolis Formation’ by Gunter (1967). For the Grand Manan Basin, the formation was named by McHone (2011) after Dwellys Cove on the southwestern shoreline, where about 8 m of mudstone, siltstone, and fine-grained sandstone are exposed directly beneath the basalt of the Southwest Head Member (Fig. 3). The formation is only found along the stony beaches of the western shoreline, with the northern end at Money Cove Head where approximately 5 m is exposed, and continuously southward except in places of talus cover, and absent for about 1 km south of Little Dark Harbour. The contact gradually lowers to below sea level near The Ladders between Dwellys Cove and Sloop Cove, and it has not been observed farther south.

Easier access to the Dwellys Cove Formation can be made along the cobble beach north from Dark Harbour, where alternating layers of pale grey siltstone and maroon clay-rich shaley mudstone 10 to 40 cm thick appear to reflect Milankovitch climate cycles (Fig. 32), as discussed by Olsen (1997). The mudstone has numerous pits and spots with remnants of light-coloured evaporite minerals including gypsum (Fig. 33). The contact with the basalt is about 6 m higher in this location, where a pale grey mudstone shows cm-thin bands of blue copper mineral stains (azurite?) in an off-white or bleached 50-80 cm thick zone directly beneath the basalt. This sub-basalt zone is more indurated, possibly a hydrothermal effect from the thick lava. Similar bleached sediment zones are noted beneath basalt elsewhere in the Fundy Basin and other rift basins (Olsen 1997), presumably due to reduction of iron oxides in the clastic matrix.

Similar layered, clay-rich siltstone is present for a few metres beneath North Mountain Basalt at Partridge Island in Nova Scotia (Olsen and Et-Touhami 2008), who include a horizon in it that marks the end-Triassic mass extinction, less than a metre beneath the basalt. The soft shaley unit is mainly confined to the uppermost 8 to 10 m of the Dwellys Cove Formation and is informally called the ‘contact member’ by McHone (2011). It resembles sediment from a playa or ephemeral lake in a semi-arid climate, as in the environment interpreted by Mertz and Hubert (1990) for the Blomidon Formation.

The most common lithology in the correlated Blomidon Formation of Nova Scotia is redbed sandstone (Mertz and Hubert 1990). This appears to be true for the Dwellys Cove Formation as well, and light red, fine-grained sandstone makes up most of the clastic part of the core on display in the Grand Manan Museum, which is missing the clay-rich contact member. The redbed strata were encountered in a 660-foot (201 m) exploration hole near Sloop Cove (western side of the island), drilled with a core during copper exploration in the 1960s (Patrick 1969). Cores from their program are preserved at Fredericton but with a small section on display at the Grand Manan Museum. The well penetrated 310 feet (94.5 m) of massive basalt, then 100 feet (30.5 m) of purple-red shale, and finally 250 feet (76.2 m) of medium sandstone (Patrick 1969). A small pavement of the redbed sandstone is exposed around beach boulders about 400 m north of Dark Harbour (Fig. 33), likewise pitted by evaporite minerals.

The Dark Harbour Basalt was introduced for the Mesozoic basalt of the Fundy Group on the Island of Grand Manan by McHone (2011). It is named after excellent exposures along the road to Dark Harbour on the west-central side of Grand Manan (Fig. 3). The basalt covers the entire island west of the Red Point border fault, except where it is on contact with a thin strip of underlying sedimentary strata of the Dwellys Cove Formation along part of the western shoreline. The Dark Harbour Basalt has been divided into three members, from bottom to top: Southwest Head Member, Seven Days Work Member, and Ashburton Head Member (Fig. 28).

The Southwest Head, Seven Days Work, and Ashburton members have petrologies similar to, and probably comagmatic with the East Ferry, Margaretsville, and Brier Island members of the North Mountain Basalt in Nova Scotia (Fig. 27, 28) described by Kontak (2008). Other descriptions of this basalt were made by Greenough (1995), who pointed out that this is one of the largest lava flows known, with an estimated 6,600 km^3 present within the Fundy Basin.

Figure 31. Mudstone and siltstone of the Dwellys Cove Formation (lower right) lying beneath columnar basalt of the Southwest Head Member of the Dark Harbour Basalt (upper right) to the north of Dark Harbour.

Figure 32. Alternating layers of mudstone and siltstone of the Dwellys Cove Formation to the north of Dark Harbour. Scale bar is 15 cm.

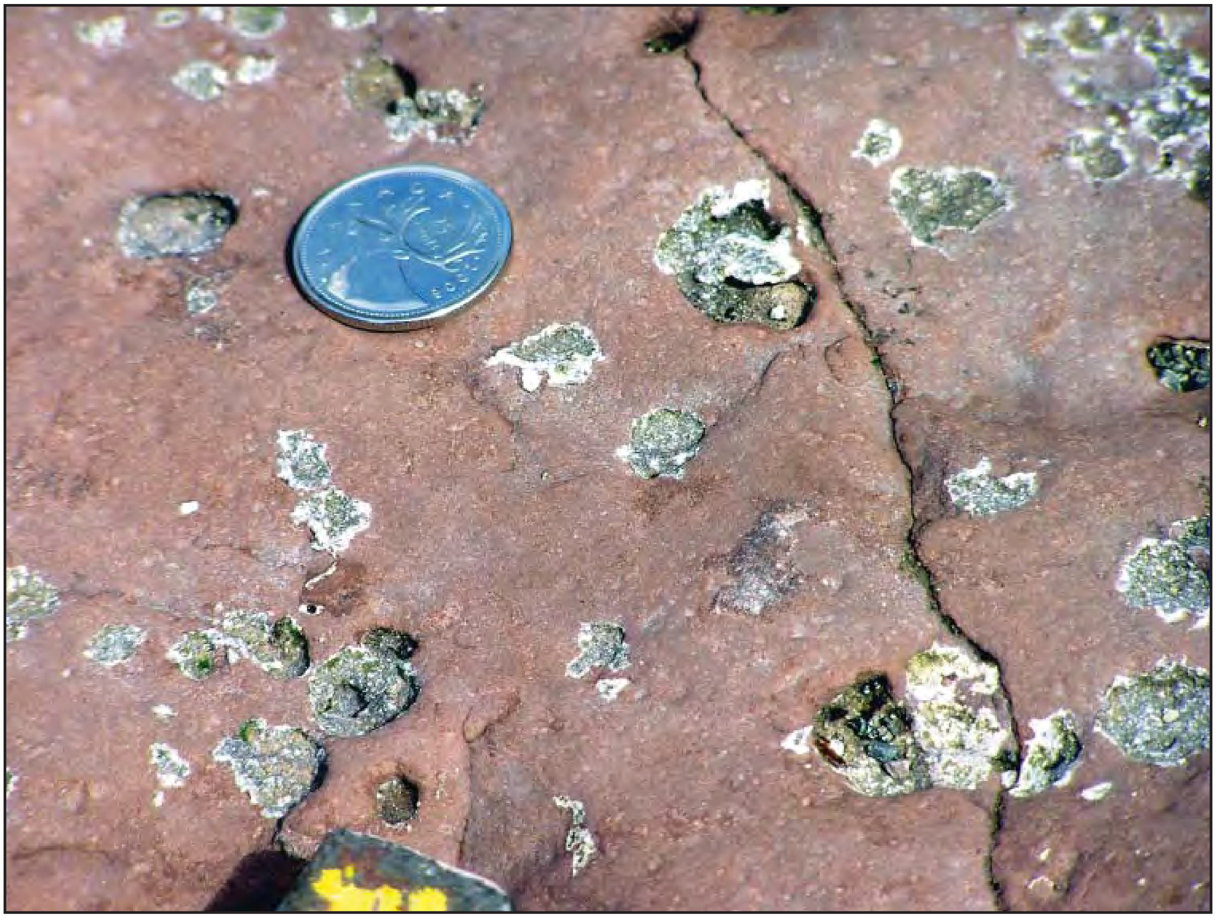


Figure 33. Brick-red sandstone Dwellys Cove Formation north of Dark Harbour, showing vugs containing evaporite minerals.

The Southwest Head Member, which is about 110 m thick along the western coast of Grand Manan, displays a colonnade or columnar structure (Fig. 34a) through its entire thickness, much like in a dyke or sill (e.g., Palisades Sill) and without the expected entablature of contorted joints. About 10 to 15 m below its top, a series of coarse segregation sheets or intrusional layers of pegmatitic pyroxene and plagioclase crystals is observed near Whale Cove and Red Point. Philpotts et al. (1996) describe the sheets as late-stage liquids squeezed upwards from a crystal mush of partially solidified basalt. The presence of segregation sheets is a useful indicator of the location within the Southwest Head Member relative to its top and bottom.

A relatively level contact between the Southwest Head Member and underlying sedimentary Dwellys Cove Formation is exposed in a long section of the western shoreline (Fig. 3). Most measurements of bedding and the contact show very modest dip angles, with less than 5° W near Dark Harbour and a few degrees southeast near Dwellys Cove. A few small hills and valleys in the contact probably reflect original surface features of the lacustrine silt and sand that were covered by the initial lava. The lava lake, represented by the Southwest Head Member, was likely sandwiched between a base of relatively dry lakebed and a thick sequence of cooled lava flows of the Seven Days Work Member overlying it (Fig. 28). As a result, the basaltic liquid of the Southwest Head Member cooled slowly and uniformly to produce its colonnade (Fig. 34b).

Figure 34a. *(above)* Columnar basalt of the Southwest Head Member of the Dark Harbour Basalt at its type locality at Southwest Head, on the Island of Grand Manan.

Figure 34 b. *(to right)* Close-up image of the great colonnade at Southwest Head. The view is to the west.

The Seven Days Work Member comprises 12 to 14 vesicular lava flows each a few metres thick, for a total thickness of approximately 70 m (Fig. 35). This member is named after a nearly complete section that occurs along shoreline cliffs local named Seven Days Work, northwest of Whale Cove (Fig. 3). Small structures in this member include pinch and swell of flows, pahoehoe lava tongues, injections of narrow dykes and sills, erosional unconformities, rubble tops and glassy contacts, gaseous pipe vesicles, lava tubes and caves, and tumulus structures (McHone 2011).

The boundary between the base of the Seven Days Work lava flows and top of the underlying Southwest Head Member is conformable but not horizontal where it is observed on the limbs of domes, broad synclines, and anticlines, which extend a few tens of metres to 1 km or more wide (Fig. 36). The limbs of these structures dip from 10°–30° toward or away from the fold axes. This deformation is not observed along the contact with underlying sedimentary strata, which suggests that the Southwest Head Member was still mostly in a liquid state when the Seven Days Work Member lavas flowed over or onto it, forming a thick, layered crust on a giant lava lake within the original rift basin. Sags, domes, ridges, and other deformation features occur in these surficial lava layers, possibly from thickness variations as well as from magmatic pressure and intrusions from below. Additional instabilities resulted from density differences in the upper part of the lava lake caused by concentrations of rising gas bubbles, which led to breakouts or dykes of vesicular basalt, and lava flows from those local sources.

The Ashburton Head Member comprises massive to columnar basalt. Its contact with the underlying Seven Days Work Member is conformable and with a gentle dip northward at its only exposed location off Dark Harbour Road. The Ashburton Head Member is interpreted to be a final and very thick lava flow, which is comagmatic but caps the entire volcanic sequence in the basin. At the type locality at Ashburton Head (Fig. 37), it is at least 80 m thick with any higher levels of the basalt and overlying sedimentary rocks probably removed by erosion. The basalt is columnar but commonly fractured, so that it is difficult to distinguish whether an entablature is developed over its colonnade.

Age Relationships and Significance of Regional Volcanism

After they were first recognized early in the 19th century, the basalts of the Fundy Basin and other Mesozoic basins of eastern North America were understood to be Triassic in age, based on a correlation with European strata or ‘New Red Sandstone’ (Bailey 1872). In the 1970s, a study of characteristic Triassic microfossils in underlying sedimentary rocks found that they did not extend upward to a position directly beneath North Mountain Basalt, whereas Jurassic fossils occurred in overlying sedimentary strata, so that the basalt was then assigned to the earliest Jurassic (Olsen 1997). Given an exact correlation of Dark Harbour Basalt with North Mountain Basalt, the same age assignment must be applied on the Island of Grand Manan.

Olsen (1997) and Olsen et al. (2005) summarized evidence that the earliest North American basin basalts erupted approximately 20,000 years after the end-Triassic mass extinction, which is placed less than a metre beneath the North Mountain Basalt in Nova Scotia at Partidge Island in the northern Fundy Basin. That extinction horizon was thought to also mark the Triassic–Jurassic boundary, making the overlying basalts Early Jurassic in age. However, Cirilli et al. (2009) found

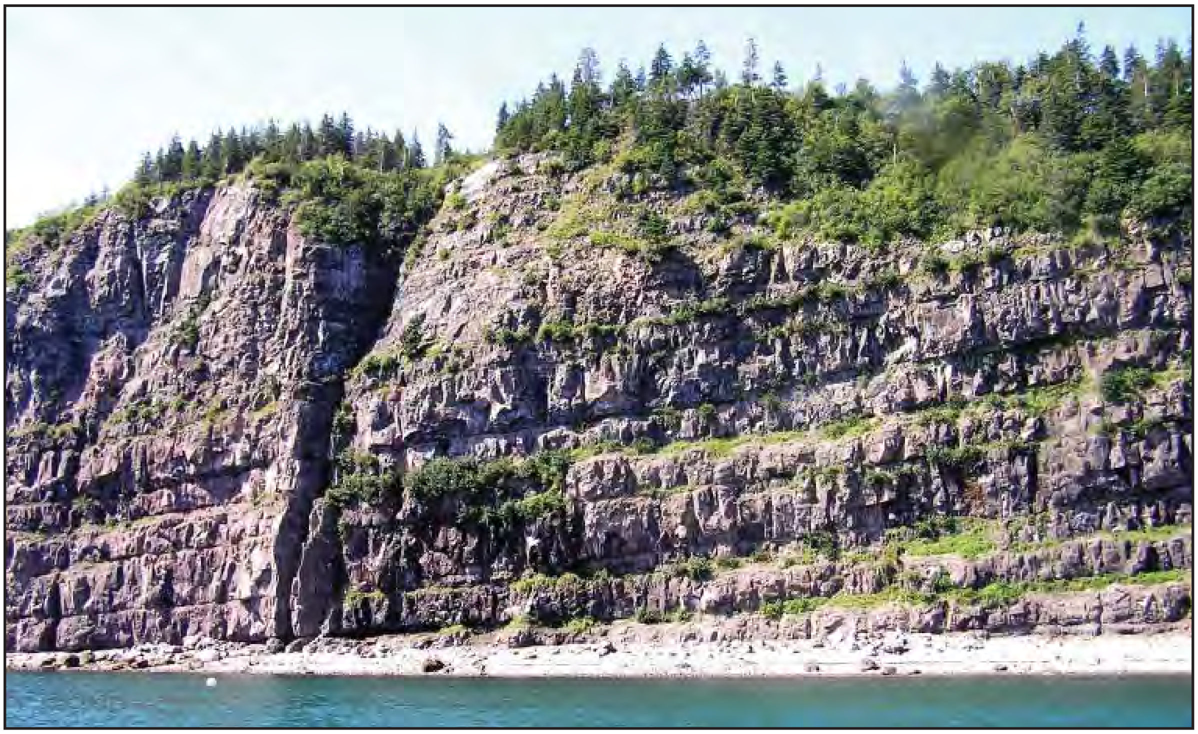


Figure 35. Vesicular lava flows of the Seven Days Work Member of the Dark Harbour Basalt at its type locality at Seven Days Work to the northwest of Whale Cove.

Figure 36. Contact between columnar basalt of the Southwest Head Member (lower left) and lava flows of the Seven Days Work Member (upper right) of the Dark Harbour Basalt on west side of Whale Cove. The uppermost basalt of the Southwest Head Member interleaves the lowest lava flows of the Seven Days Work Member (centre of photograph).

Figure 37. Highly fractured, columnar basalt of the Ashburton Head Member of the Dark Harbour Basalt at its type locality on Ashburton Head. Basalt boulders in the foreground on Eel Brook Beach have been eroded from the Seven Days Work Member.

that based on microfossils, the Triassic–Jurassic boundary is actually some tens of metres above the North Mountain Basalt, thus putting this basalt back to the latest Triassic Period as assigned before the 1970s. Although the basalt constitutes only one tholeiite-type across the Fundy Basin, it is correlated with the earliest of several basaltic magmas in other basins of northeastern North America, and it still essentially marks the division between Triassic and overlying Jurassic sedimentary and basaltic strata (Olsen 1997).

A K/Ar isochron date of 190.9 ± 2.4 Ma by Hayatsu (1979) was widely accepted as Early Jurassic and a likely cooling age for the North Mountain Basalt, until a date of 202 ± 1 Ma was reported by Hodych and Dunning (1992), who used the superior zircon U/Pb method. Recent $^{40}Ar/^{39}Ar$ dates between 199 and 202 Ma have been widely cited for most tholeiites of the Central Atlantic Magmatic Province (Marzoli et al. 1999; Olsen 1997, Jourdan et al. 2009) of which the North Mountain Basalt and regional dykes are prime examples. More precise U/Pb zircon dates of 201.27 ± 0.06 Ma (Schaltegger et al. 2008) and 201.57 ± 0.03 Ma (Blackburn et al. 2013) now date the lower unit of the North Mountain Basalt in Nova Scotia and are very close to the Triassic–Jurassic boundary as well as the end-Triassic mass extinction.

Large tholeiite intrusions of northeastern North America, including the Shelburne, Caraquet, and Christmas Cove dykes (Fig. 27), have likewise been assigned modern $^{40}Ar/^{39}Ar$ dates near 200 Ma (West and McHone 1997; Dunn et al. 1998). Their age coincidence with the great basalt flows of the basins is critical to a model in which the large dykes are fissure sources for the basalts (Philpotts and Martello 1986; McHone 1996). In southern New England, three dyke systems vary from younger to older from west to east and are sources for the three large basalts of the Hartford Basin. The eastern Higganum dyke has been demonstrated to feed the lowermost basin lava called Talcott Basalt (Philpotts and Martello 1986) which is essentially contemporaneous and comagmatic with the Fundy Basalt (Olsen 1997). The Higganum dyke connects to the Christmas Cove dyke of coastal Maine, which is co-linear and probably comagmatic with the similar Lepreau River dyke of southern New Brunswick (Fig. 27).

Blackburn et al. (2013) presented very precise dates for other basin basalts of the Central Atlantic Magmatic Province (defined by Marzoli et al. 1999), and the oldest of types similar to the Fundy Group basalts show ages that overlap for the start of the end-Triassic mass extinction, allowing them to be responsible for this major environmental catastrophe. Different areas of early volcanism probably continued to reinforce a protracted extinction event until the start of the Jurassic Period, several tens of thousands of years later, as had been suggested by Cirilli et al. (2009) and Deenen et al. (2010).

The cause–and–effect relationship of the earliest Central Atlantic Magmatic Province volcanism with the mass extinction has been strongly indicated by the newest dates as well as carbon and other isotopes related to the eruption and subsequent weathering of the massive basalts (Deenen at al. 2010; Blackburn et al. 2013). McHone (2003) estimated potential volatile emissions from CAMP volcanism with enviromental effects sufficient for the extinction event. The basalts of the Fundy Group did not start the mass extinction nor continued the catastrophe to its end, but they were among the ‘smoking guns’ of multiple massive flood basalt eruptions at the end of the Triassic Period.

Basalt and Basin Development

As mentioned above, the East Ferry, Margaretsville and Brier Island members of the North Mountain Basalt (Kontak 2008) are equivalent to the Southwest Head, Seven Days Work, and Ashburton Head members of the Dark Harbour Basalt on the Island of Grand Manan (Fig. 28). The North Mountain Basalt is present in most of the Fundy Basin and probably covered all of the basin and more but later was truncated by border faults and erosion (McHone 1996). Along the exposed eastern margin of the Fundy Basin the thickness of the North Mountain Basalt averages around 400 m (Papezik et al. 1988), but in the south-central area of the basin (east of Grand Manan) the basalt has been shown by seismic studies to be 600 to 1000 m thick (Wade et al. 1996). An average of 400 m thickness across the present basin yields a volume of 6,600 km^3 of basalt. The total thickness of basalt on Grand Manan is estimated at 240 m, but its top has apparently been removed by erosion.

In the Chinampas exploration well about 25 km northeast of the Island of Grand Manan, 333 m of basalt was drilled and divided into two units (Papezik and Greenough 1987). The lower 164 m unit has 17 ‘petrophysical cycles’ of the well log that may correspond to individual flows up to

30 m thick. The upper 169 m unit has 14 cycles with a lower cycle maximum about 70 m thick, becoming amygdaloidal in upper cycles. A weathered zone separates the two units, and other weathered layers occur in the upper unit as well (Pe-Piper et al. 1992). The well log and seismic data indicate possible clastic sediments between some flows, but these were not directly observed. The weathering and terrestrial sediments between basalt flows shows that they were subaerial.

The lava flows of Seven Days Work and Ashburton members are essentially the top crust of the initial massive lava lake that filled the present Bay of Fundy. This lava lake is represented by the Southwest Head Member, which remained mostly liquid as the two members above it were extruded and emplaced. The Southwest Head lava eventually cooled into a colonnade through its entire thickness, with the Seven Days Work Member in place of an insulating entablature. Overlying members were extruded and cooled over the liquid magma in in the Grand Manan Basin, leading to instability and the development of wide synclines and anticlines and faults from sagging and doming of the upper flows. These intra-lava deformations do not occur at the base of the Southwest Head Member. In contrast, the contact between the bottom of lava lake (the Southwest Head Member) and underlying playa-type siltstones of the Dwellys Cove Formation is generally flat-lying along 14 km of exposure on the western shoreline, with gentle dips of a few degrees evident.

Tholeiite intrusions of northeastern North America, including the Shelburne dyke of southwestern Nova Scotia, Caraquet dyke of central New Brunswick and Maine, and Christmas Cove dyke of coastal Maine (Fig. 27) have been dated by modern $^{40}Ar/^{39}Ar$ dates near 200 Ma (West and McHone 1997, Dunn et al. 1998). This age coincidence with the great basalt flows of the Mesozoic basins is critical to a model in which the large dykes are fissure sources for the basalts (Philpotts and Martello 1986; McHone et al. 1995; McHone 1996).

Thin sections and whole-rock chemical analyses indicate that the tholeiite dykes in southwestern New Brunswick are all petrologically similar (Ministers Island dyke, Buckmans Creek dyke, New River dyke, and Lepreau River dyke), and indistinguishable from the Christmas Cove dyke and Higganum-Holden-Onway dyke system of New England (McHone 1996). Photomicrographs of samples from the Lepreau River Dyke and the basalt at Dark Harbour (Fig. 38) reveal a similar petrography and forms of orthopyroxene phenocrysts, which after flow from the dyke into surface lavas became unstable and altered rapidly.

Chemical analyses of the Dark Harbour Basalt are listed with some regional Triassic dykes in Table 2. The Swallow Tail Head dyke (Table 2, No. 12 and 13) is very evolved by mafic mineral fractionation, as shown by low Cr, Ni, MgO, and other elements. As such, it is an unlikely candidate to be a source for at least the massive units of North Mountain Basalt. Much of the major and trace-element variation in tholeiitic Grand Manan basalts and dykes from the adjacent area of New Brunswick (Table 2, No. 3 to 11) can be attributed to fractionation of pyroxenes, and possibly olivine at a deeper level before eruption. Allowing for that fractionation, the Mg/Mg+Fe ratios are reasonable for a derivation as a melt of pyroxene-rich peridotitic upper mantle. In addition, variations in Sr isotopes and volatiles indicate some alteration and contamination of the tholeiite at shallow levels (Jones and Mossman 1988; Dunn and Stringer 1990).The Lansdowne dyke near Digby, Nova Scotia, (Table 2, No. 14) has a petrography consistent with either the Ministers Island or the Shelburne dyke types.

Table 2. Chemical analyses of Triassic basalts and dykes.

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Oxides														
SiO_2	51.93	53.49	50.85	52.94	52.56	52.87	52.12	51.37	51.3	52.27	52.09	53.22	51.96	45.56
TiO_2	0.87	1.06	1.13	1.14	1.19	1.21	1.31	0.83	1.12	1.00	1.21	1.51	1.54	2.09
Al_2O_3	15.28	14.94	13.83	14.13	14.46	14.77	14.31	15.43	14.76	13.8	14.34	13.54	14.17	16.02
Fe_2O_3	11.58	11.03	11.78	10.05	11.33	10.77	11.4	9.22	10.97	10.96	10.65	14.44	12.8	13.73
MnO	0.19	0.17	0.18	0.20	0.16	0.17	0.18	0.15	0.24	0.19	0.14	0.17	0.13	0.17
MgO	7.76	6.86	7.65	7.92	6.79	6.24	5.95	7.45	6.52	7.56	6.83	3.5	3.47	5.71
CaO	10.54	10.28	11.14	10.94	10.06	10.03	9.97	11.54	10.55	11.03	10.11	7.33	6.76	7.06
Na_2O	2.19	2.21	2.18	1.97	2.16	1.98	1.97	1.9	2.06	2.13	1.96	2.41	2.8	3.48
K_2O	0.50	0.75	0.63	0.55	0.75	0.83	0.76	0.43	0.42	0.67	1.32	2.12	2.08	0.38
P_2O_5	0.14	0.15	0.07	0.14	0.15	0.15	0.16	0.10	0.14	0.12	0.15	0.24	0.24	0.20
LOI			1.01		0.51	1.61	2.04	1.45	1.5	0.97	0.77	2.22	4.27	6.08
Total	100	100.9	99.9	100	100.1	100.6	100.2	99.9	99.6	100.7	99.6	100.7	100.2	100.5
Traces														
Rb	15	29	17	20	25	28	24	19	20	23	24	56	58	16
Sr	134	206	184	168	180	190	223	183	223	166	185	164	175	266
Y	27	24	18	18	22	22	23	18	22	20	22	34	33	24
Zr	66	104	107	109	103	106	117	69	102	84	102	172	174	150
Nb	6	10	10	12	9	9	10	6	8	8	10	15	15	17
Ba	134	207	175	221	72	110	62	43	26	44	89	462	721	60
Cr	118	206	284	332	154	156	100	193	131	272	166	9	12	46
Ni	50	78	82	87	66	58	98	73	69	72	60	6	3	46
V	256	254	235	262	227	228	240	175	222	210	229	264	271	315
Co			68		64	64	53	50	62	59	53	57	52	61
Cu	65	68	130		119	115	133	78	84	<4	92	5	7	85
Zn	65	78	73		83	224	83	59	156	80	89	107	97	100
Ga	14	21			15	18	17	17	18	16	17	21	23	20
Nd					22	17	15	15	<5	6	10	36	34	16
La					16	18	14	14	<5	8	8	38	37	12
Pb					5	32	2	3	2	5	4	7	34	<3
Th					5	4	4	3	3	3	4	10	10	4
U					2	2	1	2	2	2	2	1	1	<1

Notes:

Sample 1 Average Caraquet dyke, NB (Greenough and Papezik 1986)
Sample 2 Average Shelburne dyke, NS (Papezik and Barr 1981)
Sample 3 Average Christmas Cove dyke, ME (McHone, unpublished)
Sample 4 Average Ministers Island dyke, NB (Dunn and Stringer 1990)
Sample 5 Buckman's Creek dyke interior, NB (analyses by S. Barr in 2001)
Sample 6 New River dyke interior, NB (analyses by S. Barr in 2001)
Sample 7 Lepreau River dyke "A", NB (analyses by S. Barr in 2001)
Sample 8 Lepreau River dyke "B", NB (analyses by S. Barr in 2001)
Sample 9 Ashburton Head Member, island centre, NB (analyses by S. Barr in 2001)
Sample 10 Southwest Head Member, Red Point, NB (analyses by S. Barr in 2001)
Sample 11 Southwest Head Member, Dark Harbour, NB (analyses by S. Barr in 2001)
Sample 12 Swallow Tail Head dyke, interior, NB (analyses by S. Barr in 2001)
Sample 13 Swallow Tail Head dyke, southeast margin (analyses by S. Barr in 2001)
Sample 14 Lansdowne dyke near Digby, NS (analyses by S. Barr in 2001)

Oxides in weight per cent; traces in parts per million

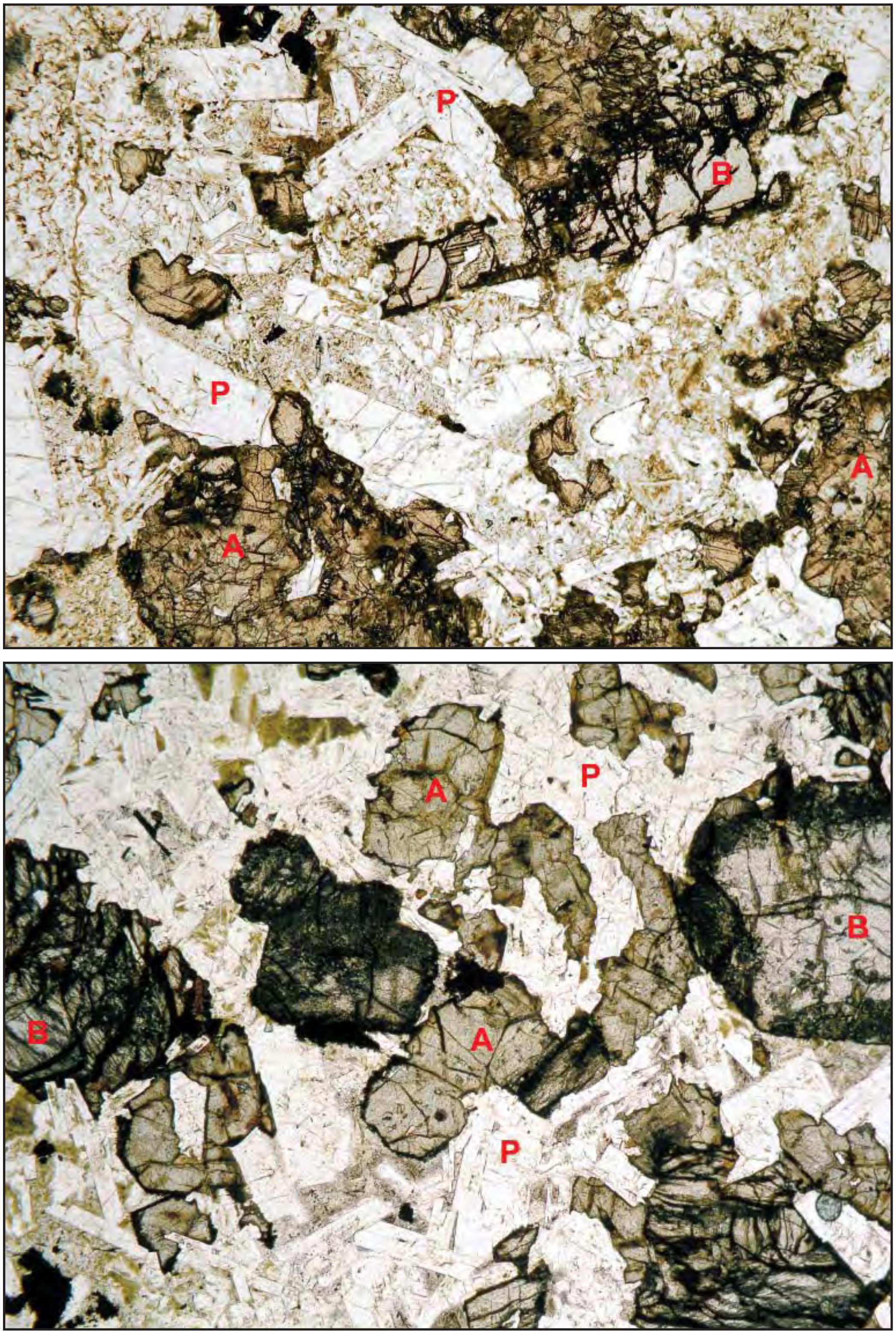


Figure 38. Photomicrographs from the interior of the Lepreau River dyke (upper image) at Buckmans Creek, and the upper part of the Southwest Head Member, Dark Harbour Basalt (lower image). The views are about 3 mm in width, under plane polarized light. Long rectangular bronzite phenocrysts (B) in the dyke are relatively clean compared with the altered orthopyroxene in the Dark Harbour basalt, which show rims darkened by opaque particles. Augite (A) grains in both samples vary in size but remain relatively fresh, as does plagioclase (P).

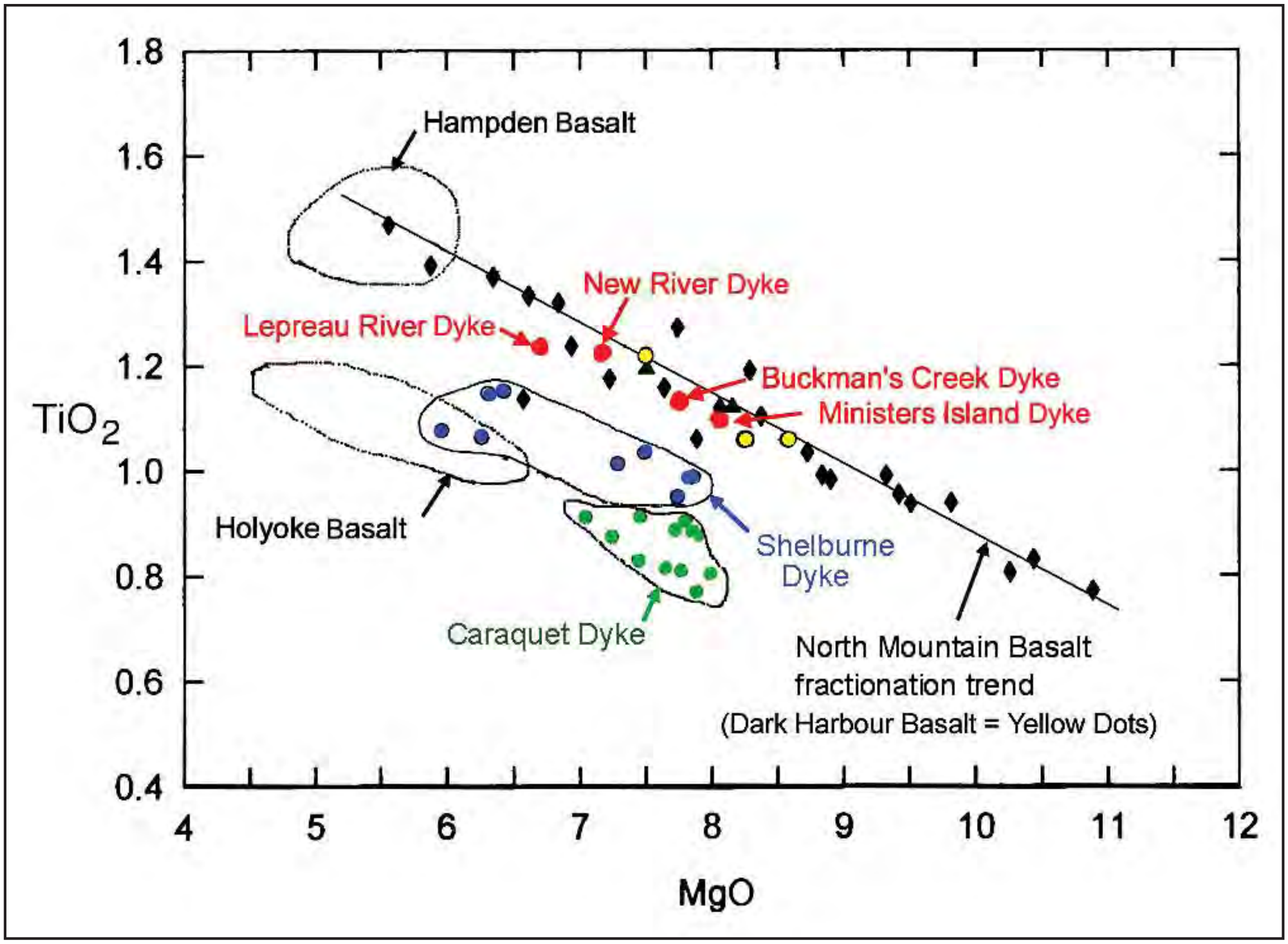


Figure 39. TiO_2–MgO variations (wt %) in Triassic basalts and dykes in the Fundy and New England regions. Compositions of the Ministers Island, Buckmans Creek, New River, and Lepreau River dykes (Table 2) coincide with a fractionation trend of North Mountain Basalt (black diamond symbols) and Dark Harbour Basalt (yellow dots). Other dykes and basalts are mainly from southern New England. Sources are Philpotts and Martello (1986); McHone (1996); and references cited in Table 2.

A TiO_2 versus MgO diagram is useful for studies of tholeiites because it is sensitive to fractionation of the mafic phenocrysts in the magmas, and thus can indicate co-magmatism along compositional trends. The Christmas Cove-Ministers Island-Lepreau River dykes as well as Dark Harbour Basalt plot on the linear trend of the North Mountain Basalt, consistent with a source-dyke relationship followed by mafic mineral fractionation in the lavas (Fig. 39). Other major dykes such as the Caraquet and Shelburne do not intersect this North Mountain Basalt trend and are different enough to be less likely sources, as discussed by McHone (1996) and Pe-Piper and Piper (1999).

Most border faults are not well exposed, which allow models in which faulting is syn-depositional, causing on-lap of clastic strata and basalt against border fault scarps. This has been called a “closed basin” model (McHone 1996). It is encouraged by the presence of fan-shaped fluvial conglomerates in basal and intermediate sections of strata close to the borders of some basins (Olsen 1997), and also by interpretations of seismic profiles (Wade et al. 1996). In addition, there are suggestions that basalts are unique to each basin and not formed from interbasin fissures with regional flows (Stevens 1987; Pe-piper and Piper 1999).

Borders of Early Mesozoic basins are defined by faults that have significant post-Triassic movement, allowing the possibility that earlier tectonism did not prevent connections of strata and basalt between basins before uplift and erosion that produced modern geographic patterns. This model has often been called ‘broad terrane’ (McHone 1996). Several lines of evidence support a broad-terrane model for this region.

- Large basins that have basaltic dykes crossing them also have large sills of the earliest generation of basalt. No sills are known in the Fundy Group strata, implying that source dykes did not cross the basins and so their flood basalts came from the large dykes mapped in adjacent regions. As discussed earlier, large dykes in southern New Brunswick are good source candidates, but which require lavas to flow outside the present basin borders.
- Basin basalts and strata immediately beneath them are matched in age and petrology in the Grand Manan and Fundy basins, and so their histories of sedimentation and basalt emplacement must be identical. The relatively shallow dips of the major-displacement border faults, and the presence of basal sandstones, indicate that the Triassic basin strata were above the modern surface of the White Head horst before faulting, The simplest conclusion is that the adjacent basin strata were originally contiguous and were separated by normal faulting along both sides of the horst after they were deposited. Basin rocks have been removed by erosion from the eastern section of Grand Manan, revealing a basement surface that was immediately beneath the lowest strata.
- Strata in the Grand Manan Basin are generally close to horizontal and not tilted downward toward a dominant normal fault, which suggests that the Murr Escarpment border fault on the western side of the basin moved equally with the eastern border Red Point Fault. That being the case, the Murr Escarpment Fault has also truncated a thick sequence of basin strata that originally extended into Maine and New Brunswick.
- Basal Triassic or older conglomeratic sandstone formations are exposed along portions of the New Brunswick coast outside (west) of the Fundy Basin (Wade et al. 1996) and also the White Head Island Horst, where they represent remnants of basin strata before border faulting produced the modern geometry of the basins. If the separate Fundy/Headlands Fault moved with the Grand Manan, Red Point, and Murr Escarpment border faults (with varying displacements), then the large Fundy Basin shares the broad-terrane depositional and tectonic history.

Part 2: Field Stop Descriptions for the Island of Grand Manan

Part 2 of this guide provides descriptions for the various stops of geological interest on the field trip. Figure 40 (p. 55) shows the stop locations on the Island of Grand Manan.

Precambrian to Early Cambrian Formations

Km (Mi)

0.0 (0.0) Exit Marathon Inn parking area in North Head turning right onto Route 776.

1.7 (1.1) Turn left off Route 776 into Stanley Road (see Fig. 40).

1.9 (1.2) Park near shore and walk to the right up Stanley Beach to outcrops of Flagg Cove Formation (Castalia Group).

STOP A1: Stanley Beach
Flagg Cove Formation and Stanley Brook Granite

Thin- to medium-bedded, graded, light grey to greyish pink quartzose sandstones and green to dark grey shales of the Flagg Cove Formation are complexly folded and contain the trace fossil *Planolites* on some bedding surfaces. A coarse-grained cataclastic granite (Stanley Brook Granite) is in sheared contact with sandstone and a thick grit bed of the Flagg Cove Formation farther along the section. Narrow veins of granite and quartz transect the sedimentary rocks near the granite contact.

2.1 (1.3) Return on Stanley Road to Route 776 and turn left.

2.9 (1.8) Turn left off Route 776 into private driveway just prior to Dock Road visible to the right.

3.0 (1.9) Bear right past house with bright red roof to shore.

STOP A2: The Dock
Great Duck Island Formation

Great Duck Island Formation (Castalia Group) forms this prominent point known as The Dock. Maroon conglomerate several metres thick is interstratified with lenses of darker maroon to olive green sandstone and silty shale intervals about a metre thick. Bedding (S_0) trends 130° and dips 80° SW. Pebbles and cobbles are mainly pinkish grey and white quartzite ranging in size from 1 cm to 12 cm. Grading in sandstone beds indicates younging to the northeast.

3.1 (2.0) Return to Route 776 and turn left.

5.4 (3.3) Park vehicles at mailboxes on left side of Route 776 in Castalia and take path to shore.

STOP A3: Castalia
Priest Cove Formation

Greyish green volcaniclastic sandstone of the Priest Cove Formation (Castalia Group) is exposed on the shore. Beds grade from coarse sand with rip-up clasts at the base into laminated silt at the top indicating younging to the northeast. S_0 generally trends 150° and dips 50° NE; S_2 cleavage trends 0° and dips 45° W; and F_2 folds plunge 25° toward 135°.

Turn left onto Route 776.
9.0 (5.6) Turn left off Route 776 onto Breakwater Drive in Woodwards Cove.
9.3 (5.8) Bear left past M&G Fish Plant and park near pond on the left side of the shore road. Walk 200 m north along shore.

STOP A4: Ragged Point
Contact between Ingalls Head and Priest Cove formations

Highly schistose exposures of light grey, felsic lithic tuff are interstratified with dark green mafic tuff locally containing steel grey magnetite-rich lenses. The penetrative S_2 cleavage trends 160° and dips 50° SW. These volcanic rocks are lithologically identical to the dated Neoproterozoic Ingalls Head Formation (Grand Manan Group) that will be seen later on Ingalls Head.

Following a 100 m gap in outcrop, medium-grained, greyish green, plagioclase-phyric gabbro intrudes volcaniclastic sandstone of the Priest Cove Formation on Ragged Point. S_0 varies from 95°/ 70° SW to 120° / 75° SW; S_2 cleavage in the trends 135° and dips 50° SW. The unexposed contact between the Ingalls Head and Priest Cove formations is assumed to be faulted in this section.

9.6 (6.0) Return on Breakwater Drive to Route 776 and turn left.
10.1 (6.3) Turn left off Route 776 in Woodwards Cove onto Shore Road to Priest Cove.
12.4 (7.7) Stop A5

STOP A5: The Thoroughfare
The Thoroughfare Formation

A prominent outcrop of massive white quartzite of The Thoroughfare Formation (Grand Manan Group) is accessible by crossing the bridge over to the eastern shore of The Thoroughfare onto the northern tip of Ross Island. The faulted contacts between the The Thoroughfare, Ingalls Head, and Priest Cove formations can be observed on the western shore of The Thoroughfare just to the north of the lobster ponds the faulted. This section begins in black graphitic shale and medium-bedded grey quartzite of The Thoroughfare Formation; here S_0 trends 20° and dips 30° E and S_1 trends 115° and dips 80° N. A thick quartz vein, presumably marking a steep fault zone, separates The Thoroughfare Formation from a sequence of greyish green feldspathic sandstone, maroon silty shale, and minor felsic tuff to the north. This sequence is correlated with the Ingalls Head Formation (Grand Manan Group) but an alternative correlation with the Great Duck Island Formation (Castalia Group) is also possible; here bedding (S_0) trends 70° and dips 30° S and is inverted; S_2 trends 135° and dips 50° SW; and L_2 fold axes plunge 25° toward 140°.

Still farther north, greyish green volcaniclastic sandstone of the Priest Cove Formation (Castalia Group) structurally underlies the Ingalls Head Formation. S_0 in the volcaniclastic sandstone trends 170°and dips 80° E but tops to the west. A shear zone dipping 30° E separates the Priest Cove Formation from the structurally overlying Ingalls Head Formation. Secondary shear bands trending 35° and dipping 35° NW are consistent with west-directed thrust movement.

14.7 (9.1) Return on Shore Road to Route 776 and turn left.
17.8 (11.0) Turn left off Route 776 in Grand Harbour onto Ingalls Head Road.
20.5 (12.7) Turn right off Ingalls Head Road onto Brownville Road.
20.8 (12.9) Bear right onto Ox Head Road.
22.0 (8.1) Park on Ox Head and walk east along shore.

STOP A6: Ox Head
Ingalls Head Formation

Highly schistose olive green dacitic tuff containing fragments from 1 cm to 2 cm in size and thin, maroon magnetite-rich beds and lenses characterize the Ingalls Head Formation (Grand Manan Group). The tuffs are interstratified with massive greyish pink rhyolite flows about a metre thick, one of which yielded a zircon date of 618 ± 3 Ma. Olive green to purple volcanic breccias containing green and maroon, angular felsic volcanic fragments from 1 to 15 cm in size are exposed farther to the east.

26.2 (16.2) Return to Route 776 and turn left.
28.8 (17.9) Turn left off Route 776 onto Anchorage Road.
29.7 (18.4) Bear left onto Long Pond Road.
30.4 (18.8) Turn left at T-junction on Long Pond Bay.
31.0 (19.2) Park at east end of Long Pond.

STOP A7: Long Pond
Ingalls Head Formation

Pink felsic flow on shore contains large spherulites (2 to 3 cm in diameter) cored by quartz. This isolated outcrop yielded a zircon date of 618 ± 3 Ma proving it to be part of the Ingalls head Formation.

31.6 (19.6) Return to T-junction and leave vehicles in parking lot. Walk approximately 300 m southwest along Long Pond Bay.

STOP A8: Long Pond Bay
Long Pond Bay Formation

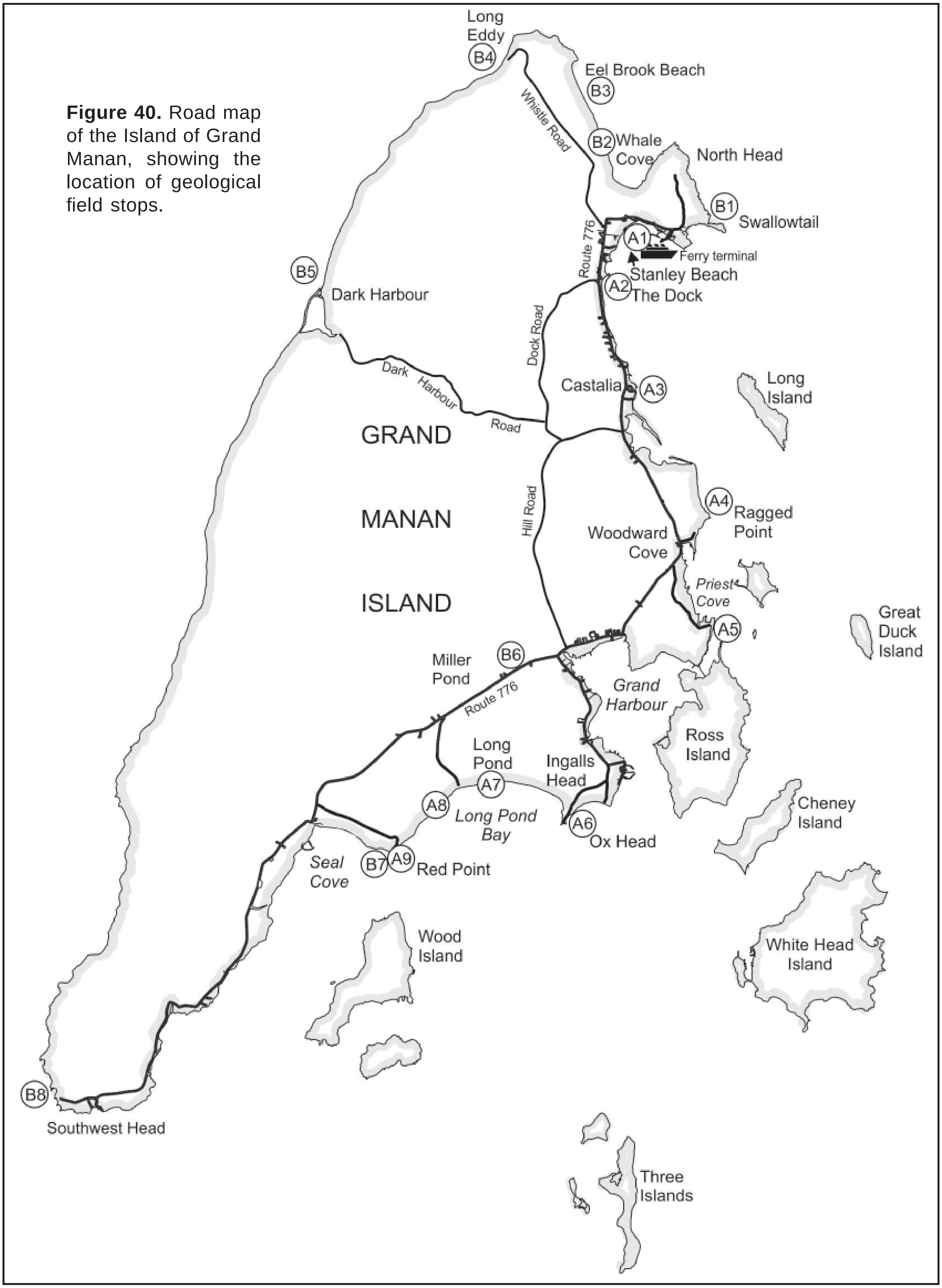
The outcrop on the shoreline consists of complexly folded, grey feldspathic sandstone and silty shale of the Long Pond Bay Formation (Castalia Group). Beds vary from 15 to 20 cm in thickness and grade upward from a coarse sandy base, containing rip-up clasts of underlying shale, into a laminated shale interval at the top; S_0 varies in orientation from 100° / 75° NE to 60° / 70° NW , S_1 trends 120° and dips 40° NE, and L_1 plunges 35° toward 50°. Another 300 m along the shore, grey siltstone interlaminated with fine-grained, grey sandstone is locally interstratified with conglomeratic breccia (10 m thick), containing angular fragments (1–10 cm in length) of laminated siltstone; S_0 trends 15° and dips 75° NW and S_2 trends 120° and dips 80° SW. Another 200 m southwest along the shore, mafic hyaloclastic tuff is in contact with a black shale mélange containing large blocks (2 m in size) of sandstone.

33.2 (20.6) Return to Route 776 and turn left.
36.5 (22.6) Turn left off Route 776 in Seal Cove onto Red Point Road.
38.5 (23.9) Park in picnic area at end of the Red Point Road. Walk down trail to the beach on the south side of Red Point.

STOP A9: Red Point
Long Pond Bay Formation

The steep, northeasterly trending, normal Red Point Fault separates reddish-stained, laminated siltstone of Long Pond Bay Formation from Jurassic basalt to the west. S_0 in the siltstone varies from a strike of 60° and dip of 40° NW to a strike of 75° and dip of 70° NW. Interstratified mafic flows, bedded hyaloclastic tuffs, and laminated siltstone of the Long Pond Bay Formation are exposed continuously for 800 m along the shore to the northeast. A series of thrusts trending about 90° and dipping 50° N divides the sequence into a number of fault slices. Mafic dykes transecting the section have irregular margins suggesting that they were injected prior to complete consolidation of the host rocks.

Figure 40. Road map of the Island of Grand Manan, showing the location of geological field stops.



Triassic Formations

Km (Mi)

0.0 (0.0) Exit Marathon Inn parking area in North Head and turn left onto Route 776 (see Fig. 40).

0.6 (0.4) Turn left onto Old Airport Road. Pettes Cove will be on the right. Just before you go up the hill toward Hole in the Wall Park, turn right onto Lighthouse Road.

1.5 (0.9) Park near the overlook and walk down the stairway onto the footbridge.

STOP B1: Swallow Tail Head
Sawpit Dyke and North Head Formation

The large rusty dyke (Fig. 17) is hosted by Early Cambrian (?) North Head Formation, which is low-greenschist-grade metamorphosed basalt of the eastern basement horst, and formerly beneath the basin strata and basalt before they were down-dropped by the Red Point Fault. Gunter (1967) and Ernst et al. (2003) suggested that it is a feeder to the Mesozoic lava flows. However, in thin section, it lacks the strong mafic mineral content of the other Mesozoic dykes in the region, with fewer augite grains scattered among abundant feldspars (mainly sodic plagioclase), and no orthopyroxene. Its subalkaline chemistry is also too different (Table 2). Although the rock is somewhat altered, it does not appear to be foliated or metamorphosed. It has abundant iron oxide minerals, which cause the rich rust-brown colour as well as divert compass needles to a small degree.

The dyke strikes N31º E (watch for compass aberration), dips 74º SE, and is about 29 m wide at the bridge. The dyke is split by erosion in the ravine, with about 2/3 of the northwestern part of the dyke leaning as a massive unit against the cliff, and the southeastern third mostly removed. This might indicate a multiple or composite intrusion, but we have not observed internal chill margins.

Jelle de Boer drilled core plugs from the eroded section near the water in 1999 for magnetic study, and they show a near-vertical AMS orientation (Ernst et al. 2003). The dyke has not been traced to the southwest, so it might be truncated by a brittle fault that runs along the southern edge of Swallow Tail Head (Fyffe et al. 2011a), which itself may be cut by the Red Point Fault near Whale Cove (Fig. 3).

The Sawpit Dyke might be a member of an Early Triassic subalkaline basaltic dyke group that appears intermittently in coastal regions of northeastern North America (McHone 1992; Pe-Piper et al. 1992). It appears too well preserved to be Paleozoic. Perhaps a plagioclase concentrate from the dyke would yield a reasonable Ar/Ar plateau date, for which I would be happy to provide a sample.

The North Head Formation that hosts the dyke is composed of dark grey, massive mafic volcanic flows and breccia (Fyffe et al. 2011a). It is only slightly foliated from effects of low-grade greenschist metamorphism, not quite greenstone, and with fractures that make a rough and irregular surface. The formation is part of the Castalia Group, which has a few zircon dates of 535 to 547 Ma or Early Cambrian to latest Ediacaran (Miller at al. 2007). The Fish Head Formation bordering it to the north has some similarity but is more gabbroic and somewhat foliated.

Thin seams of sulphide minerals (mainly galena) are present east of the Swallow Tail Light Keepers House. Along the shore a few hundred metres north of Swallow Tail Head are thick (0.2-1 m) veins of white and pink barite mixed with quartz, some of which has been excavated.

Return back to Route 776 and travel west through North Head village.
3.7 (2.2) Turn right onto Whale Cove Road and drive to the end.
4.7 (2.9) Park at the end of the road but do not block the fishermen's boat ramp. Walk along the grassy bluff above the cobble beach, then down onto the beach to cliffs of Southwest Head Member of Dark Harbour Basalt, and north along the cobbles to see its features and contact with the overlying Seven Days Work Member.

STOP B2: Whale Cove
Southwest Head and Seven Days Work members

Along the beach is the upper part of the great colonnade that characterizes the Southwest Head Member. Note the presence of some bands or layers of much coarser basalt, almost pegmatitic with acicular clinopyroxene grains up to several centimetres long. These are segregation sheets (Philpotts et al. 1996), which are formed from late stage liquid that intrudes the uppermost part of thick lava flows, while migrating from the collapse of the feldspar network of the basalt after it has partially crystallized. They typically appear near top of a large basalt flow or sill, which makes them a useful marker in an otherwise featureless colonnade of tholeiite.

The top of this member is another 50 m or so along the beach. We are on the south limb of a wide syncline along the cliff to the north called Seven Days Work. Here, the lavas dip toward the northeast. Seven Days Work has a fine display of the middle member of the Dark Harbour Basalt, consisting of 12 or more amygduloidal pahoehoe-type lava flows, most a few metres thick but varying between <1 m to 12 m. Examine the lowest flow of this member in contact with the Southwest Head Member.
It is easy to see the differences between these two basalt members, with the relatively altered, thinner, and gas-rich lava flows resting on much more solid gray

basalt. Look from the beach to the face at the contact. A layer of the lower massive basalt runs up the left side, and then turns sharply downward to the right to intrude between the lowest lava flows of Seven Days Work. The basalt beneath Seven Days Work was still liquid when the initial flow above had hardened into a layered crust. That crust was floating on a great magma lake that filled the Fundy Basin, and the two members have been mixed here. Crusts of solid lava over smaller lava lakes have been studied in Hawaii, and in the crater of Kilauea it was possible to drive a drill rig out onto it to sample the magma beneath.

Return to Route 776 and turn right.

5.8 (3.6) Turn right at Tattons Corner onto Whistle Road.

8.9 (5.5) Park in front of boulders on the right (east side) of the road, which block two former entrances into an old dump. The trail to Eel Brook Beach starts on the right just to the north of the dump. It is about 1 km to the shoreline, where there is a short but steep drop down to Eel Brook Beach, which is a ‘shingle beach’ of flat cobbles of basalt. To the north is the Ashburton Head Member while to the south is the Seven Days Work Member -- their type localities.

STOP B3: Eel Brook Beach
Ashburton Head and Seven Days Work members, contact fault

The basalt of the Ashburton Head Member is partly columnar like the Southwest Head Member, but in this upper member much of the colonnade is deformed and broken by faults. A low-angle fault at the base of the cliff looks like the upper part was thrust along at a shallow angle. Also look closely at the dark gash that runs at an angle up the cliff, near the head end. It appears to be filled a narrow dolerite dyke, which indicates the continued presence of magma beneath the upper members of the Dark Harbour Basalt. It has been too difficult to get a close view and sample.

A low-angle normal fault with thick gouge toward the northern end of the beach separates the Seven Days Work Member from the Ashburton Head Member. Note the physical contrast between the two members. The fault surface dips 49° NE with a trend that curves from about 280° to 330° around Ashburton and Northern Head, emerging at Whistle Beach (*Stop B4*). The Ashburton Head Member has moved down the fault with a vertical displacement of about 60 m to 80 m, judging from the thickness of the adjacent Seven Days Work Member. The deformation visible in the cliff face may be due to the fault movement as well as from instability over the Fundy lava lake. We can discuss this from evidence at the next stops.
Around the point the Ashburton Head colonnade is more vertical, and it may have a true entablature in its upper part, but if so the contact with the colonnade is not very

distinct. The Ashburton Head Member is at least 80 m thick at Northern Head, with its upper surface apparently removed by erosion. This member is mapped only in the highest part of the northern third of Grand Manan (Fig. 3), indicating a simple `layer cake` geometry of members of the Dark Harbour Basalt.

Walk south along the cobble beach to the start of the Seven Days Work cliffs. This is a good place for a hard hat. Rocks fall often down these cliffs, and you should try to stay some distance out from their base for safer geologizing.

The Seven Days Work Member is named after this spectacular cliff about 60 to 80 m high along the western side of Whale Cove. The name is derived from its lava layers with the notion that one layer was built per day (Allaby 1984). There are actually 12 or more flows visible, but they vary with pahoehoe tongue ends, pinch and swell, and cross-cutting features. The Red Point Fault extends offshore from beneath Whale Cove Beach, as traced by the fault-line scarp west of the highway from North Head to Seal Cove (Fig. 3). The fault must connect somehow to the northern Grand Manan Basin border east of Passamaquoddy Bay, but there are few clues available for its exact pattern beneath the sea.

Unlike the massive basalt members below and above it, Seven Days Work flows are relatively thin (≤1 to ~12 m) amygduloidal lavas that are typically altered to gray and oxidized brown colours, in places showing the remains of dense former glass in their surfaces. The amygdules are filled with minerals (mainly zeolites) that precipitated out of hot fluids, and these fluids also altered and corroded the basalt.

Perhaps the most interesting of these amygdule minerals belong to the zeolite group, which are alkali-alumino-silicates that have water molecules trapped in their crystalline structures. They have commercial uses such as in water softeners, but mineral collectors provide their value here. Zeolites that you can find at Seven Days Work include mesolite (scolecite), heulandite, stilbite, and chabazite. White to pale pink needle-like crystals of mesolite occur in masses that radiate in fans and cone-like forms (see photos in the minerals section). Mesolite is difficult to distinguish from its close relative scolecite, which was the name used for fine examples at the Grand Manan museum, but scolecite (the calcium end member) is generally rare. The sodium end member, with this same form, is called natrolite.

Seven Days Work minerals also include many forms of quartz and chalcedony, including amethyst, white banded agate, gray, blue, and striped agate, many colours of jasper, aventurine, onyx, and no doubt others. Pockets can show interior zones of agate and amethyst surrounded by blue-green aventurine and a rim of dark green celadonite.

Gas-charged tubes called pipe vesicles are common near the base of some flows, the result of exsolved volatiles rising from the lava bottom as it solidified (Philpotts and Lewis 1987). The pipes can rise 10 to 20 cm or more and are filled with mixtures of calcite, zeolites, and late basaltic magmas. Several small pipes may join together as they rise. Pipe vesicles can be deformed by the final movement of the lava they rise through, in which case they provide flow directions (little indication of that here).

There are small lava tubes with a cave about half way along the cliff base toward Whale Cove. It only goes in a couple of metres, so it was probably opened by wave erosion. Above the cave is the round end of a lava tube that is still completely filled by gray basalt. It contrasts in colour with the vesicular lava flows, which are weathered to a more rusty violet-red hue. A small dyke runs upward from the tube.

10.5 (6.5) Return to Whistle Road and continue northward to the end of the road. Park by the bench down the hill below Long Eddy Light (also known as 'The Whistle'). The ramp is used by fishermen, so do not park in any way that might obstruct their vehicles.

Continue northeast around the sea wall and along the boulder beach.

STOP B4: Long Eddy
Seven Days Work Member, Whistle Beach Fault, Ashburton Head Member

The basalt below the overlook and lighthouse is the same Seven Days Work Member of the Dark Harbour Basalt that was examined at *Stop B3.* Past the cobble beach is a good cliff exposure of Seven Days Work flows, but these rocks are especially unstable and people should stay away from the cliff base as much as possible. Less than 100 m northeast of the lighthouse, a sloping contact crosscuts the amygdaloidal flows. It appears to strike SSE and dip 45° ENE, across which is the massive Ashburton Head Member that extends around Northern Head.

This site was interpreted by Gunter (1967) to represent an intrusional contact, with the massive unit cross-cutting the thinner flows. However, map patterns show that this is the same fault as encountered at northern Eel Brook Beach, where Ashburton Head basalt has clearly slid down against Seven Days Work flows. Moreover, there is tectonic basalt breccia generated along and nearby the fault. Columns of Ashburton Head basalt are bent against the fault, a drag fold structure also seen at Red Point and Indian Beach. It must be that both basalt members solidified, and the overlying Ashburton Head basalt slid down along this fault contact by about 80 m against solid lava layers beneath it.

Yet, there is a problem with this simple interpretation. Look closely at the fault. Little empty tubes bend upward into the fine-grained basalt directly above the contact. They are pipe vesicles, made from gases streaming up from the base of liquid basalt as it solidified. This is an igneous contact, not a fault contact. But the Seven Days Work layers are clearly crosscut by the Ashburton Head Member, and we know this is a fault at its Eel Brook Beach end. How is that possible?

The answer may be that this feature is both a fault contact and also an igneous contact. The normal fault formed first, causing the drag fold and basalt breccia. The fault was then injected by basaltic magma from the lava lake below (a dyke), and the pipe vesicles formed as the dyke cooled (presumably under low pressure). The dyke is about a half metre wide and continues up the fault until it is lost to view in brush. These features might have formed close together in time, but before the lava lake that would become the lower Southwest Head Member was completely solid.

Return to the boat ramp. If time and tide permit, continue southwest along the boulder beach toward Indian Beach, which ends at the sea wall off the point in the distance. Be warned, this is a long and difficult hike.

STOP B4 (cont'd): Seven Days Work and Southwest Head members, volcanic dyke-to-flow outcrop, breccia dykes, contact fault and folds

The beach is slow going because of the areas where boulders of basalt have fallen from the low cliffs. Being struck by rocks or twisting your ankle on the cobbles are hazards at any time. We once watched a rock slide go crashing down not far in front of us along here, raising a cloud of dust. Beware!

The cliffs show layers or lava flows of the Seven Days Work Member of the Dark Harbour Basalt. They do not seem to have as many zeolites and other collector attractions as does the section below the cliffs of Seven Days Work, but beach pebbles of white banded agate as well as rare blue agate and common red-brown jasper are found here.

Observe the particularly massive lava flow in the cliff face, which is about 12 m thick. As you make your way SW over the beach stones, it will warp down to the beach level, where you can see some small pipe vesicles, or tubes made by gases escaping from the base of the flow (see the Seven Days Work excursion). They tilt toward the southwest, indicating the final direction of flow as it cooled.
About 1 km of travel brings you past The Gully, a break in the cliff face with a weir by the same name offshore from it. About 50 m farther, the large lava flow in the cliff face abruptly bends to plunge downward, cutting through the lava flows beneath.

Of course, the lava likely moved up to make the flow, not down to make the dyke. This is an extremely rare exposure where a dyke is observed to feed a lava flow, and we are looking at a cross section of the volcanic vent of the fissure. One other such dyke-to-flow exposure is known in the Hartford Basin of Connecticut, where the Fairhaven Dyke is observed to connect with the Talcott Basalt (Philpotts and McHone 2003).

The dyke is about 8 m wide and trends southeasterly into the cliff. As proposed at other stops, the relatively thin lavas of Seven days Work were extruded onto a solid crust above a large liquid magma lake, which became the Southwest Head Member of the Dark Harbour Basalt. That magma lake is the source of this dyke, and of some other smaller intrusions elsewhere. Other dykes must feed other thin flows of the middle member. The movement of this lava flow from its source is contrary to the tilt of the pipe vesicles mentioned above. Perhaps lava near the dyke ended its flow by moving a little backward into the vent, as has been observed in Hawaii. Present tilting of the Indian Beach Dyke and along the Gully Flow probably occurred after their emplacement.

Along its south side and also cutting into the igneous dyke are smaller intrusions of red sandstone or clastic breccia dykes, some mixed with small blocks of basalt. The breccia dykes were probably powered by steam, which would eject explosively from moist sediment or groundwater beneath the lava. The small dykes could only penetrate through the overhead lava after it hardened, of course. It might seem that arkosic sand beneath the lower flow would have to rise too far through the thick lower basalt into the middle member, but a little farther to the southwest is a fault, and on its far side the sediment under the basalt may be less than 10 m to 20 m beneath the beach. The clastic dykes also incorporated pieces of basalt from their wall rocks as they moved upward and across the fault into the hanging wall.

That Indian Beach Fault is about 40 m farther south along the shore. It has dropped the Seven Days Work Member and overhead Ashburton Head Member about 70 m down on its northeast side. The fault surface is poorly exposed under rubble and vegetation, but it appears to dip about 75° NNE (a normal fault) and strike roughly ESE. That puts it about on-line with the Pettes Cove Fault mentioned at *Stop B1*. It is difficult to trace across the island because the upper rock types on either side of it are similar and outcrops are poor.

Note how the Seven Days Work lava flows are tilted up against the fault in a big drag fold. The exact contact with overlying Ashburton Head Member basalt is high in the cliff and hard to distinguish except from a distance. On the southern footwall side of the fault, the Southwest Head Member has a closely spaced joint set about parallel with the fault. Similar joint sets appear at locations where the western cliff is set back from the coastline, which possibly erode to make the `heads` that can be seen from the ferry when it is north of the island.

Return to the parking area at the end of Whistle Road. Drive back to Tattons Corner and bear right onto Route 776, heading south.

17.0 (10.5) Just past the Nursing Home, turn right (west) onto Dock Road. The Red Point Fault runs along and beneath Route 776 in this area, and Dock Road rises up the fault-line scarp of the Red Point Fault through the Southwest Head Member. At the top the road levels off in a long topographic bench that is underlain by level lava flows of the Seven Days Work Member.

20.7 (12.8) Turn right onto Dark Harbour Road. The road rises through upper levels of the Seven Days Work Member.

23.0 (14.2) The road crests Laborie Hill with a low road cut of Ashburton Head Member basalt on the north side. On the hillside to the south is a quarry in highly-weathered Seven Days Work basalt, and the contact with overlying Ashburton Head basalt is visible near the top of the quarry wall. The road descends into Great Valley, which is a swampy area underlain by the fairly level Seven Days Work flows.

25.4 (15.7) Dark Harbour Overlook: The upper part of the Southwest Head Member colonnade is quarried across the road, and from here the road descends with a vertical section about 90 m through this member, to the shoreline behind the great sea wall of Dark Harbour. Samples from this cut were described by Pe-Piper and Piper (1999) as being chemically similar to the lower massive basalt unit across Fundy Bay at Digby, Nova Scotia, named the East Ferry Member by Kontak (2008).

We have not been able to detect layering or separate flows in this unit, so it represents a single flow or lava body about 120 m in thickness. Slight tilt of the colonnade basalt shows a very gentle dip of a few degrees eastward in this area.

26.4 (16.3) If the tide is low it is possible to drive along the beach strand below the camps to the northern end of Dark Harbour, near the old wooden tower. Park and turn around carefully while staying on the strand, because your vehicle will sink into the mud on the water side. If the tide is high or approaching high, park above the small wharf at the base of the road (do not block access by fishermen who must use this wharf) and walk along the beach strand to the north.

STOP B5: Dark Harbour
Dark Harbour Basalt, Dwellys Cove Formation, end-Triassic extinction horizon

Where the basalt talus does not cover it, gray to dull maroon and buff-coloured soft shale, siltstone, and mudstone are exposed along the beach beneath the basalt. This sedimentary rock is closely correlated with the uppermost Blomidon Formation of the northern Bay of Fundy (Wade and Jansa 1994), which here is named Dwellys Cove Formation after a locally known copper-bearing exposure farther south (McHone 2011). As in the Blomidon Formation along the northern shore of the Minas Basin, the mudstone unit is the uppermost member of the formation, called in Nova Scotia the Partridge Island Member (Olsen et al. 2005). At this location an informal name of `contact member' has been used by McHone (2011).

The contact member apparently was deposited in a playa-type environment, or seasonal arid-climate lake (Mertz and Hubert 1990). Spots of light-coloured gypsum attest to very saline or alkaline water, due to high rates of evaporation. The climate here was very hot and dry around 201 Ma (Olsen 1997), but a monsoon season allowed lakes to form. Lighter and darker layers in the sediment record shallower and deeper lake levels as the climate slowly fluctuated in 20,000 year Milankovitch orbital cycles (Olsen et al. 2005).

The contact with the basalt is about 7 m above this location, where a soft dusty pale grey mudstone shows cm-thin bands of blue copper-mineral stains (azurite?), capping an off-white or bleached 40-80 cm thick zone that is slightly harder or indurated, possibly as a hydrothermal effect under the basalt. Similar bleached sediment zones are noted beneath basalt elsewhere in the Fundy Basin and other rift basins, with the colour presumably due to reduction of iron oxides in the clastic matrix.

In the bleached zone perhaps 20 cm or so beneath the basalt is a stratigraphic layer above which there is a major loss in Triassic biodiversity, followed by a different group of new species over the next few million years (Olsen et al. 2005). It marks the start of the end-Triassic mass extinction, which may have continued in pulses or stages for 100,000 years or more (Deenen et al. 2010). The end of the extinction event and start of the Jurassic Period is placed some 10s of metres above the North Mountain Basalt by Cirilli et al. (2009), in the McCoy Brook Formation (no equivalent is at Grand Manan).

About 0.7 km along the shore north of Dark Harbour a pavement of fine grained red sandstone crops out on the beach beneath the contact member. Unlike the soft shale above, the rock is solid enough to make round boulders. This is the only place we have seen this ‘shoreline member’ but cores drilled up to 100 m beneath the basalt shows that it continues at least that deep (Patrick 1964). Here less than a metre is exposed, which is conformable but physically contrasts with the overlying contact member. In addition, this pavement marks the end of the TS-3 and start of the TS-4 tectonostratigraphic units of Olsen et al. (2005).

Both members show surface pits where evaporite minerals such as salt have been washed out, and off-white patches that appear to be gypsum.

Return on Dark Harbour Road to Dock Road and turn right.
33.5 (20.7) Turn right onto Hill Road. Continue to the end of this road in Grand Harbour.
38.2 (23.6) Turn right (south) onto Route 776.
39.9 (24.6) Turn right onto Miller Pond Road.
40.0 (24.7) Park in the abandoned gravel quarry on the left (south) side of the road. Walk to the southeast side of the cleared area and down the bank on that side to small exposures of red sandstone.

STOP B6: Miller Pond Road
Miller Pond Road Formation

Alcock (1948) noted the presence of “minor amounts of reddish and brownish sandstone and conglomerate” a few kilometres to the southwest of Grand Harbour, which he mapped as beneath the basalt along the western side of the Red Point Fault. This sandstone was relocated by McHone in the spring of 2010, exposed partly under brush along a bank on the southeastern side of this abandoned gravel quarry off Miller Pond Road.

The sandstone bedding dips about 5°–10° NE, and by traveling from the NE toward the SW about 10 m along the bank, the sandstone grades into lower levels from poorly-lithified medium-grained red sandstone to an even more weakly-cemented sharpstone conglomerate containing abundant small gray phyllite or foliated gray quartzite clasts, then into a clast-supported breccia or paleo-regolith dominated by the same type of rock clasts, which are very similar to surface fragments of the Long Pond Bay argillite. The angular rock fragments in the sandstone preserve a fabric or preferred orientation that might represent original cleavage or foliation in the bedrock, which appears to be dipping toward the north more steeply than the sandstone bedding.

The field evidence indicates that the sandstone was deposited upon and grades into the top of the Long Pond Bay Formation, although solid bedrock of this basement rock is not locally exposed. Surface exposures of this metamorphic basement rock are observed to be brecciated into present-day angular gravel at Red Point and elsewhere, apparently a function of rock cleavages and fracture patterns. The exact appearance of the unconformity at this location is obscured by vegetation and the intermixing of the formations in the paleoregolith.

The Miller Pond Road Formation is very similar to sandstone of the Lepreau Formation near Maces Bay on the mainland coast north of Grand Manan, which Olsen (1997) considers to be Late Permian in age even though it represents the base of the Early Mesozoic basin strata (Unit TS-1 of Olsen et al. 2005).

Return to Route 776 and turn right (south).

44.7 (27.6) Turn left onto Red Point Road, which is not far south of Seal Cove village.

46.8 (28.9) Park in the far end of the lot and walk down the trail a short distance, then down onto the beach.

STOP B7: Red Point
Basin border fault, Southwest Head Member

This point and shoreline to the north expose the Long Pond Bay Formation of Early Cambrian (?) age, which here is argillite (metasiltstone), but not far along the beach are rocks developed from volcanic ash and mud (Fyffe et al. 2011a). The Red Point Fault is well exposed in the wave-cut bank about 100 m west of the parking lot. The fault extends from here NE and then N to Whale Cove, separating Triassic basalt on the west from the much older eastern basement formations. Friction or drag from the fault movement has bent and broken the basalt columns, which originally were nearly vertical. At this location the fault strikes about N50ºE and dips about 72º NW.

The weathered iron-oxide colour of the fine grained argillite on the eastern foot wall of the fault gives the point its name. On the upper hanging wall side of the fault, the basalt columns have been bent and brecciated by fault movement into a low angle against the fault surface. The Red Point Fault runs under the soils north to Whale Cove, and out under the sea in both directions to form the eastern border for the Grand Manan Basin (McHone 2011).

Vertical offset is estimated from the observation that the bottom of the basin strata (Miller Pond Road Formation) east of the fault is nearly at the same level as the top of the strata (Dwellys Cove Formation) west of the fault, thus the vertical offset of the fault nearly matches the thickness of the sub-basalt strata. As discussed earlier, the deep exploration hole Chinampas N-37 in the Fundy Basin northeast of

Grand Manan intersected Triassic sub-basalt strata about 2,950 m thick (Papezik and Greenough 1987), which may approximate the thickness in the Grand Manan Basin. This would also be the vertical offset of the Red Point Fault.

A few metres west from the fault, the colonnade becomes more upright and more typical of the Southwest Head Member of the Dark Harbour Basalt. About 150 m toward Seal Cove Beach to the southwest, the Seven Days Work Member appears, so here we must be fairly close to the top of the lower member. This is also indicated by segregation sheets like those examined at *Stop B2*, which occur in the upper section of basalt sheets.

Return to Route 776 and turn left.

49.3 (30.4) Bridge over "the creek" in Seal Cove Village with amygdaloidal flows of the Seven Days Work Member. Continue south to the end of the road.

65.0 (40.1) Park in the circular lot near the light house and radio tower. Walk NW along the clifftop trail just far enough to see the basalt cliffs. Avoid the edge, which is very unstable. The highway ends at an automated lighthouse and radio tower.

STOP B8: Southwest Head
Southwest Head Member, colonnade

Park in the circular lot near the lighthouse and radio tower. Walk NW along the clifftop trail just far enough to see the basalt cliffs. Stay away from the edge, which is very unstable. The highway comes to an end at an automated lighthouse and radio tower.

The spectacular cliffs of columnar basalt at this location soar 70 m above the surf, whereas to the west the Grand Manan Basin is under the Grand Manan Channel, with its western margin along the distant shoreline of Maine. Late Triassic lava flows are now completely absent from coastal Maine, although their source is exposed along it as a great basaltic dyke.

The cliffs expose the Southwest Head Member, which is lower part of the Dark Harbour Basalt. The columnar structure or colonnade extends through the entire unit, and this was once a single thick lava flow that filled and 'ponded' in the wide valley, which much later became the Bay of Fundy and still holds around 6,600 km^3 of basalt. No lava flow of this size is known in historic times: a good thing, as this one might have made a world-wide environmental disaster.

Large basaltic lavas in other regions continue the Greek temple architecture theme with an 'entablature' over the colonnade, but here that is missing. Instead, we have the multiple flows of Seven Days Work, which apparently formed upon the top crust of the liquid lava lake that later became the Southwest Head Member.

The columns formed as the basalt cooled and contracted, and because heat flowed vertically toward the top and bottom of the flow, the columns were originally nearly vertical as well. Now their tops tilt slightly to the northeast, which indicates a gentle warping of the upper basalt units. A series of shallow-dipping fractures break the columns across the face of the cliffs. Additional fractures parallel to the original cooling fractures cause a “splintery” effect in much of the colonnade.

The great colonnade resembles the Palisade Sill north of New York City and other large basalt sills in Connecticut, and an early proposal was that this basalt at Southwest Head is also a great sill (Gunter 1967; Allaby 1984). However, the evidence that it was a formed as a lava flow on the surface is compelling, both here and across the Bay of Fundy where identical basalts are found (Kontak 2008). Actually, the Palisades Sill and the Southwest Head Member of Grand Manan are very similar in age and composition, and both are part of the same gigantic volcanic event that produced all of the earliest dykes, sills, and basalts in Mesozoic basins of northeastern North America near the end of the Triassic Period.

Grand Manan Ferry Trip

When viewed from the ferry as it passes Swallow Tail Head, the Sawpit Dyke stands out by its brown colour and its horizontal cooling columns are visible against the cliff on the north side. After the boat passes Fish Head, the numerous amygdaloidal flows of Seven Days Work can be seen to contrast with the massive lower and upper basalt units off to the distant sides. Examination of the flows from this perspective shows how they form a shallow syncline about 1 km wide, with its axis trending west to northwest.

As the boat proceeds to the north, we can see a series of headlands along the western side of the island, which appear as steps in the top of the basalt cliffs. At least some of these steps are along eroded tectonic zones within the massive lower basalt unit, with closely spaced, near-vertical joints and possibly faults that postdate with the magmatic activity.

Nearer to Blacks Harbour, islands known as The Wolves appear not far to the east of the ferry track. They are comprised of Early Silurian monzodiorite (Wolczanski et al. 2007) and are immediately west of the Fundy Basin border fault, and (apparently) in a northern section of the same basement horst that makes up the eastern rocks of Grand Manan.

To the west on a clear day, Little White Horse Island can be seen from the ferry as it gets closer to Blacks Harbour (also see it via Google Earth). The entire island is essentially a 350 m long by 110 m wide section of the Lepreau River Dyke. The dyke crops out at several other places along a linear magnetic anomaly from the Lepreau River to Deadmans Harbour in southern New Brunswick, and it also appears on-line at Indian Island not far from Eastport, Maine. Greg McHone with Sandra Barr and Bill Hames are proposing that this dyke was the major source of the Fundy Group Basalts (manuscript in progress).

If you wish to visit the Lepreau River Dyke, a good outcrop is in the south bank of Buckman's Creek near the highway not far north of Beaver Harbour, first described by Helmstaedt (1968).

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References

Alcock, F.J. 1938. Geology of Saint John region, New Brunswick. Canada Department of Mines and Resources, Mines and Geology Branch, Geological Survey of Canada, Memoir 216, 65 p.

Alcock, F.J. 1948. Grand Manan, New Brunswick. Geological Survey of Canada, Map 965A.

Allaby, E. 1984. Grand Manan. Grand Manan Museum, Inc., Grand Harbour, 64 p.

Bailey, L.W. 1872. On the physiography and geology of the Island of Grand Manan. Canadian Naturalist, 6, pp. 42–54.

Barnhardt, W.A., Belknap, D.A., Kelley, A.R., Kelley, J.T., and Dickson, S.M. 1996. Surficial geology of the Maine inner continental shelf: Petit Manan Point to West Quoddy Head. Maine Geological Survey Map 96–13.

Barr S.M., and Raeside, R.P. 1989. Tectono-stratigraphic terranes in Cape Breton Island, Nova Scotia; implications for the conFiguration of the northern Appalachian orogen. Geology, 17, pp. 822–825.

Barr, S.M. and White, C.E. 1996a. Contrasts in late Precambrian-early Paleozoic tectonothermal history between Avalon composite terrane *sensu stricto* and other possible peri-Gondwanan terranes in southern New Brunswick and Cape Breton Island, Canada. *In* Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic. *Edited by* R. D. Nance and M.D. Thompson. Geological Society of America Special Paper, 304, pp. 95–108.

Barr S.M., and White, C.E. 1996b. Tectonic setting of Avalonian volcanic and plutonic rocks in the Caledonian Highlands, southern New Brunswick, Canada. Canadian Journal of Earth Science, 33, pp. 156–168.

Barr, S.M., and White, C.E. 1999. Field relations, petrology and structure of Neoproterozoic rocks in the Caledonian Highlands, Southern New Brunswick. Geological Survey of Canada Bulletin, 530, 101 p.

Barr, S.M., Bevier, M.L., White, C.E., and Doig, R. 1994. Magmatic history of the Avalon Terrane of southern New Brunswick, Canada, based on U–Pb (zircon) geochronology. Journal of Geology ,102, pp. 399–409.

Barr, S.M., White, C.E., and McLeod, M.J. 1997. Geology of the Kingston Peninsula, southern New Brunswick: a preliminary report. *In* Current Research 1996. *Edited by* B.M.W. Carroll. New Brunswick Department of Energy and Mines, Mineral Resource Report 97-4, pp. 1–20.

Barr, S.M., Raeside, R.P. and White, C.E. 1998. Geological correlations between Cape Breton Island, Nova Scotia and Newfoundland, northern Appalachian orogen. Canadian Journal of Earth Sciences, 35, pp. 1252–1270.

Barr, S.M., White, C.E., and Miller, B.V. 2002. The Kingston Terrane, southern New Brunswick, Canada: Evidence for an Early Silurian volcanic arc. Geological Society of America Bulletin, 114, pp. 964–982.

Barr, S.M., Miller, B.V., Fyffe, L.R., and White, C.E. 2003a. New U–Pb Ages from Grand Manan and the Wolves Islands, Southern New Brunswick. *In* Current Research 2002. *Edited by* B.M.W. Carroll. New Brunswick Department of Energy and Mines, Mineral Resource Report 2003-4, pp. 13–22.

Barr, S.M., Davis, D.W., Kamo, S. and White, C.E. 2003b. Significance of U–Pb detrital zircon ages in quartzite from peri-Gondwanan terranes, New Brunswick and Nova Scotia, Canada. Precambrian Research **126**, pp. 123–145.

Barr, S.M., White, C.E., and Miller, B.V. 2003c. Age and geochemistry of Late Neoproterozoic and Early Cambrian igneous rocks in southern New Brunswick: Similarities and contrasts. Atlantic Geology, 39, p. 55–73.

Barr, S.M., Mortensen, J.K., White, C.E., and Friedman, R.M. 2010. Age and petrology of the Machias Seal Island quartz monzodiorite, the southernmost rocks in New Brunswick, Canada. Atlantic Geology 46, pp. 155–172.

Barr, S.M., Hamilton, M.A., Samson, S.D., Satkoski, A.M., and White, C.E. 2012. Provenance variations in northern Appalachian Avalonia based on detrital zircon age patterns in Ediacaran and Cambrian sedimentary rocks, New Brunswick and Nova Scotia, Canada. Canadian Journal of Earth Sciences, 49, pp. 533–546.

Bartsch, C.J., and Barr, S.M. 2005. Distribution and petrochemistry of Late Neoproterozoic rocks in the southwestern New River Terrane, southern New Brunswick. *In* Geological Investigations in New Brunswick for 2004. *Edited by* G.L. Martin. New Brunswick Department of Energy and Mines, Mineral Resource Report 2005–1, pp. 1–22.

Bevier, M.L. and Barr, S.M. 1990. U–Pb age constraints on the stratigraphy and tectonic history of the Avalon Terrane, New Brunswick, Canada. Journal of Geology, 98, pp. 53–63.

Bevier, M.L., White, C.E., and Barr, S.M. 1990. Late Precambrian U–Pb ages for the Brookville Gneiss, southern New Brunswick. Journal of Geology, 98, pp. 955–965.

Black, R. 2005. Pre-Mesozoic geology of Grand Manan Island, New Brunswick. Unpublished M.Sc. Thesis, Acadia University, Wolfville, Nova Scotia, 227 p.

Black, R.S., Barr, S.M., Fyffe, L.R., and Miller, B.V. 2004. Pre-Mesozoic rocks of Grand Manan Island, New Brunswick: Field relationships, new U–Pb ages, and petrochemistry. *In* Geological Investigations in New Brunswick for 2003. *Edited* by G.L. Martin. New Brunswick Department of Energy and Mines, Mineral Resource Report 2004-4, pp. 21–40.

Blackburn, T.J., Olsen, P.E., Bowring, S.A., McLean, N.M., Kent, D.V., Puffer,J., McHone, J.G., Rasbury, E.T., and Et-Touhami, M. 2013. Zircon U–Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province. Science, 340 , pp. 941–945.

Cirilli, S., Marzoli, A., Tanner, L., Bertrand, H., Buratti, N., Jourdan, F., Bellieni, G., Kontak, D., and Renne, P. R. 2009. Latest Triassic onset of the Central Atlantic Magmatic Province (CAMP) volcanism in the Fundy Basin (Nova Scotia). New stratigraphic constraints. Earth and Planetary Science Letters, 286, pp. 514–525.

Currie, K.L. 1987. Late Precambrian igneous activity and its tectonic implications, Musquash-Loch Alva region, southern New Brunswick. *In* Current Research, Part A. Geological Survey of Canada, Paper 87-1A, pp. 663–671.

Currie, K.L. 1991. A note on the stratigraphy and significance of the Martinon Formation, Saint John, New Brunswick. In Current Research, Part D. Geological Survey of Canada, Paper 91-1D, pp. 9–13.

Currie, K.L., and Eby, G.N. 1990. Geology and geochemistry of the late Precambrian Coldbrook Group near Saint John, New Brunswick. Canadian Journal of Earth Science 27, pp. 1418–1430.

Currie, K.L. and Hunt, P.A. 1991. Latest Precambrian igneous activity near Saint John, New Brunswick *In* Radiogenic Age and Isotopic Studies: Report 4. Geological Survey of Canada, Paper 90-2, pp. 11–17.

Currie, K.L. and McNicoll, V.J. 1999. New data on the age and geographic distribution of Neoproterozoic plutons near Saint John, New Brunswick. Atlantic Geology, 35, pp. 157–166.

Dallmeyer, R.D., Doig, R., Nance, R.D., and Murphy, J.B. 1990. $^{40}Ar/^{39}Ar$ and U–Pb mineral ages from the Brookville Gneiss and Green Head Group: Implications for terrane analysis and evolution of Avalonian 'basement' in southern New Brunswick. Atlantic Geology, 26, pp. 247–257.

Dalziel, I.W.D. 1997. Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation. Geological Society of America Bulletin, 109, pp. 16–42.

da Silva, L.C., McNaughton, N.J., Armstrong R., Hartmann, L.A., and Flecher, I.R. 2005. The Neoproterozoic Mantiquerira Province and its African connection: A zircon-based U–Pb geochronologic subdivision for the Brasiliano/Pan-African system of orogens. Precambrian Research, 136, pp. 203–240.

Deenen, M.H.L., Ruhl, M., Bonis, N.R., Krijgsman, W., Kürschner, W.M., Reitsma, M., and Van Bergen, M.J. 2010. A new chronology for the end-Triassic mass extinction. Earth and Planetary Science Letters, 291, pp. 113–125.

Dickson, S.M., Kelly, J.T., and Barnhardt, W.A. 1994. Geomorphology and sedimentary framework of the Inner Continental Shelf of Downeast Maine. Maine Geological Survey, Open File Report 94-11, 55 p.

Doig, R., Nance, R.D., Murphy, J.B., and Casseday, R.P. 1990. Evidence for Silurian sinistral accretion of Avalon terrane in Canada. Journal of the Geological Society, London, 147, pp. 927–930.

Dunn, T. and Stringer, P. 1990, Petrology and petrogenesis of the Ministers Island dyke, southwest New Brunswick, Canada. Contributions to Mineralogy and Petrology, 105, pp. 55–65.

Dunn, A.M., Reynolds, P.H., Clarke, D.B., and Ugidos, J.M. 1998. A comparison of the age and composition of the Shelburne dyke, Nova Scotia, and the Messejana dyke, Spain. Canadian Journal of Earth Sciences, 35, pp. 1110–1115.

Eby, G.N. and Currie, K.L. 1993. Petrology and geochemistry of the Kingston complex - a bimodal sheeted dyke suite in southern New Brunswick. Atlantic Geology, 29, pp. 121–135.

Eby, G.N., and Currie, K.L. 1996. Geochemistry of the granitoid plutons of the Brookville terrane, Saint John, New Brunswick and implications for the development of the Avalon Zone. Atlantic Geology 32, pp. 247–268.

Ernst, R. E., de Boer, J.Z., Ludwig, P., and Gapotchenko T. 2003. Magma flow pattern in the North Mountain basalts of the 200 Ma CAMP event: Evidence from the magnetic fabric. *In* The Central Atlantic Magmatic Province: Insights from fragments of Pangea. *Edited by* W. Hames, J.G. McHone, P. Renne, and C. Ruppel. American Geophysical Union Monograph Series,136, pp. 227–239.

Fyffe, L.R. and Grant, R.H. 2001. Precambrian and Paleozoic geology of Grand Manan Island. *In* Guidebook to Field Trips in New Brunswick and Eastern Maine. *Edited by* D. Lentz and R. Pickerill New England Intercollegiate Geological Conference, Fredericton, New Brunswick, Trip A-5, 13 p.

Fyffe L.R., Pickerill, R.K., and Stringer, P. 1999. Stratigraphy, sedimentology and structure of the Oak Bay and Waweig formations, Mascarene Basin: implications for the paleotectonic evolution of southwestern New Brunswick. Atlantic Geology, 35, pp. 59–84.

Fyffe, L.R., Barr, S.M., Johnson, S.C., McLeod, M.J., McNicoll, V.J., Valverde-Vaquero, P., van Staal, C.R., and White, C.E. 2009. Detrital zircon ages from Neoproterozoic and Early Paleozoic conglomerate and sandstone units of New Brunswick and coastal Maine: Implications for the tectonic evolution of Ganderia. Atlantic Geology, 45, pp. 110–144.

Fyffe, L.R., Grant, R.H, and McHone J.G. 2011a. Geology of Grand Manan Island (parts of NTS 21B/10 and B/15), New Brunswick. New Brunswick Department of Energy and Mines, Map Plate 2011-14.

Fyffe, L.R., Johnson, S.C., and van Staal, C.R. 2011b. A review of Proterozoic to Early Paleozoic lithotectonic terranes in the northeastern Appalachian orogen of New Brunswick, Canada, and their tectonic evolution during Penobscot, Taconic, Salinic, and Acadian orogensis. Atlantic Geology, 47, p. 211–248.

Fyffe, L.R., van Staal, C.R., Valverde-Vaquero, P., and McNicoll, V.J. 2011c. U–Pb Age of the Stanley Brook Granite, Grand Manan Island, New Brunswick, Canada. Atlantic Geology, 47, pp. 1–8.

Gesner, A. 1839. First report of the geological survey of New Brunswick. Section on Grand Manan reprinted in The Grand Manan Historian, no. 23 (1981), pp. 8–21.

Greenough, J.D. 1995. Mesozoic rocks. *In* Geology of the Appalachian–Caledonian orogen in Canada and Greenland. *Edited by* H. Williams. Geological Society of America, The Geology of North America, F-1, Chapter 6, pp. 567–600.

Greenough, J.D. and Papezik V.S. 1986. Petrology and geochemistry of the early Mesozoic Caraquet dyke, New Brunswick, Canada. Canadian Journal of Earth Sciences, 23, pp. 193–201.

Greenough, J.D., McCutcheon, S.R., and Papezik, V.S. 1985. Petrology and geochemistry of Cambrian volcanic rocks from the Avalon Zone in New Brunswick. Canadian Journal of Earth Sciences, 22, pp. 881–892

Gunter, W.D. 1967. Feldspars from a tholeiite sill, Grand Manan, New Brunswick, M.Sc. thesis, University of New Brunswick, Fredericton, N.B., 130 p.

Hayatsu, A. 1979. K–Ar isochron age of the North Mountain Basalt, Nova Scotia. Canadian Journal of Earth Sciences, 16, pp. 973–975.

Hayes, A.O. and Howell, B.F. 1937. Geology of Saint John, New Brunswick. Geological Society of America Special Paper, 5, 146 p.

Helmstaedt, H. 1968. Structural analysis of the Beaver Harbour area, Charlotte County, New Brunswick. Unpublished Ph.D. thesis, University of New Brunswick, Fredericton, New Brunswick, 196 p.

Hewitt, M.D. 1993. Geochemical constraints on the sources of sedimentary and volcanic sequences, Grand Manan Island, New Brunswick. B. Sc. thesis, Department of Geology, Hartwick College, Oneonta, New York, U.S.A., 20 p.

Hibbard, J.P., van Staal, C.R., Rankin, D.W., and Williams, H. 2006. Lithotectonic map of the Appalachian Orogen (North), Canada–United States of America; Geological Survey of Canada, Map 02042A.

Hilyard, M. 1992. The geologic significance of Grand Manan Island, New Brunswick. B. Sc. Thesis, Department of Geology, Hartwick College, Oneonta, New York, U.S.A., 26 p.

Hodgins, M.L. 1994. Trace elements, REE and Nd isotopic variations in metavolcanic and metasedimentary sequences, Grand Manan Island, New Brunswick. B. Sc. thesis, Department of Geology, Hartwick College, Oneonta, New York, U.S.A., 33 p.

Hodych, J.P. and Dunning, G.R. 1992. Did the Manicouagan impact trigger end-of-Triassic mass extinction? Geology, 20, pp. 51–54.

Hofmann, H. J. 1974. The stromatolite *Archaeozoon acadiense* from the Proterozoic Greenhead Group of Saint John, New Brunswick. Canadian Journal of Earth Sciences, 11, pp. 1098–1115.

Johnson, S.C. 2001. Contrasting geology in the Pocologan River and Long Reach areas: implications for the New River belt and correlations in southern New Brunswick and Maine. Atlantic Geology, 37, pp. 61–79.

Johnson, S.C. and McLeod, M.J. 1996. The New River Belt: A unique segment along the western margin of the Avalon composite terrane, southern New Brunswick, Canada. *In* Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic. *Edited by* R.D. Nance and M.D. Thompson. Geological Society of America Special Paper, 304, p. 149–164.

Johnson, S.C. and Barr, S.M. 2004. New chemical data from Neoproterozoic–Cambrian igneous rocks in the Long Reach area, southern New Brunswick. *In* Geological Investigations in New Brunswick for 2003. *Edited by* G.L. Martin. New Brunswick Department of Energy and Mines, Mineral Resource Report 2004–4, pp. 75–94.

Johnson, S.C., Fyffe, L.R., McLeod, M.J., and Dunning, G.R. 2012. U–Pb ages, and tectonomagmatic history of the Cambro–Ordovician Annidale Group: a remnant of the Penobscot arc system in southern New Brunswick. Canadian Journal of Earth Sciences, 49, pp. 166–188.

Jones, L. M. and Mossman, D. J. 1988. The isotopic composition of strontium and the source of the Early Jurassic North Mountain basalts, Nova Scotia. Canadian Journal of Earth Sciences, 25, pp. 942–944.

Jourdan, F., Marzoli, A, Bertrand, H., Cirilli, S., Tanner, L.H., Kontak, D.J., McHone, J.G., Renne, P.R., and Bellieni, G. 2009. $^{40}Ar/^{39}Ar$ ages of CAMP in North America: Implications for the Triassic–Jurassic boundary and the ^{40}K decay constant bias. Lithos, 110, pp. 167–180.

Keen, C.E., Kay, W.A., Keppie, D., Marillier, F., Pe-Piper, G., and Waldron, J.W.F. 1991. Deep seismic reflection data from the Bay of Fundy and Gulf of Maine: Tectonic implications for the northern Appalachians. Canadian Journal of Earth Sciences, 28, pp. 1096–1111.

Kennedy, W.Q. 1964. The structural differentiation of Africa in the Pan-African tectonic episode (± 500 m.y.). University of Leeds, Institute of African Geology Report, 8, pp. 48–49.

Kontak, D.J. 2008. On the edge of CAMP: Geology and volcanology of the Jurassic North Mountain Basalt, Nova Scotia. Lithos, 101, pp. 74–101.

Landing, E., Bowring, S.A., Davidek, K.L., Westrop, S.R., Geyer, G., and Heldmaier, W. 1998. Duration of the Early Cambrian: U–Pb ages of volcanic ashes from Avalon and Gondwana. Canadian Journal of Earth Sciences, 35, pp. 329–338.

Landing, E., Johnson, S.C., and Geyer, G. 2008. Faunas and Cambrian volcanism on the Avalonian marginal platform, southern New Brunswick. Journal of Paleontology, 82, pp. 884–905.

Leech, G.B., Lowdon, J.A., Stockwell, C.H., and Wanless, R.K. 1963. Age determinations and geological studies (including isotopic ages - Report 4). *In* Geological Survey of Canada, Paper 63-17, pp.103–104.

Léger, A., and Williams, P.F. 1986. Transcurrent faulting history of southern New Brunswick. *In* Current Research, Part B. Geological Survey of Canada, Paper 86-1B, p. 111–120.

Lowdon, J.A., Stockwell, C.H., Tipper, H.W., and Wanless,R.K. 1963. Age determinations and geological studies (including isotopic ages – Report 3). *In* Geological Survey of Canada, Paper 62-17, p.13.

MacNaughton, R.B. and Pickerill, R.K. 1995. Invertebrate ichnology of the nonmarine Lepreau Formation (Triassic), southern New Brunswick, Eastern Canada. Journal of Paleontology, 69, pp. 160–171.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., and De Min, A. 1999. Extensive 200 million-year-old continental flood basalts of the Central Atlantic Magmatic Province. Science, 284, pp. 616–618.

McHone, J.G. 1992. Mafic dyke suites within Mesozoic igneous provinces of New England and Atlantic Canada, *In* Eastern North American Mesozoic Magmatism. *Edited by* J.H. Puffer and P.C. Ragland. Geological Society of America Special Paper, 268, pp. 1–11.

McHone, J.G. 1996. Broad-terrane Jurassic flood basalts across northeastern North America. Geology, 24, pp. 319–322.

McHone, J.G. 2001. Mesozoic geology of Grand Manan. *In* Guidebook to Field Trips in New Brunswick and Eastern Maine. *Edited by* D. Lentz and R. Pickerill. New England Intercollegiate Geological Conference, Fredericton, New Brunswick, Trip B-6, 16 p.

McHone J.G., 2003, Volatile emissions of Central Atlantic Magmatic Province basalts: Mass assumptions and environmental consequences. *In* The Central Atlantic Magmatic Province. *Edited by* W. E. Hames, J.G. McHone, P. Renne, and C. Ruppel. American Geophysical Union Monograph Series, 136, pp. 241–254.

McHone, J.G. 2011. Triassic basin stratigraphy at Grand Manan, New Brunswick, Canada. Atlantic Geology, 47, pp. 125–137.

McHone, J.G. and McHone, N.W. 2012. Grand Manan Geology: Excursions in Island Earth History. Stones2Gems Publications, North Head, 55 p.

McHone, J.G., West, D.P., Jr., Hussey, A.M., II., and McHone, N.W. 1995 The Christmas Cove dyke, coastal Maine: Petrology and regional significance. Geological Society of America, Abstracts with Programs, 27, pp. 67–68.

McLeod, M.J. 1995. Bedrock geology and metallic mineral occurrences in the Letang–Head Harbour Passage area, Charlotte County, New Brunswick. *In* Current Research 1994. *Compiled and Edited by* S.A.A. Merlini. New Brunswick Department of Natural and Energy, Minerals and Energy Division, Miscellaneous Report 18, pp. 141–156.

McLeod, M.J. and McCutcheon, S.R. 1981. A newly recognized sequence of possible Early Cambrian age in southern New Brunswick: Evidence for major southward-directed thrusting. Canadian Journal of Earth Sciences, 18, pp. 1012–1017.

McLeod, M.J., Ruitenberg, A.A. and Krough, T.E. 1992. Geology and U–Pb geochronology of the Annidale Group, southern New Brunswick: Lower Ordovician volcanic and sedimentary rocks formed near the southeastern margin of Iapetus Ocean. Atlantic Geology, 28, pp. 181–192.

McLeod, M.J., Johnson, S.C., and Ruitenberg A.A. 1994. Geological map of southwestern New Brunswick, Canada. New Brunswick Department of Energy and Mines, Map Plate NR-5.

McLeod, M.J., Johnson, S.C., and Krogh, T.E. 2003. Archived U–Pb (zircon) dates from southern New Brunswick. Atlantic Geology, 39, pp. 209–225.

Mertz, K.A. and Hubert, J. 1990. Cycles of sand-flat sandstone and playa-mudstone in the Triassic–Jurassic Blomidon red beds, Fundy rift basin, Nova Scotia: Implications for tectonic and climatic controls. Canadian Journal of Earth Sciences, 27, pp. 442–451.

Miller, B.V., Barr, S.M., and Black, R.S. 2007. Neoproterozoic and Cambrian U–Pb (zircon) ages from Grand Manan Island, New Brunswick: Implications for stratigraphy and northern Appalachian terrane correlations. Canadian Journal of Earth Sciences, 44, pp. 911–923.

Murphy J.B., van Staal, C.R., and Keppie J.D. 1999. Middle to Late Paleozoic Acadian Orogeny in the northern Appalachians: a Laramide-style, plume-modified orogeny. Geology, 27, pp. 653–656.

Nadon, G.C., and Middleton, G.V. 1984. Tectonic control of Triassic sedimentation in southern New Brunswick: local and regional implications. Geology, 12, pp. 619–622.

Nadon, G.C., and Middleton, G.V. 1985. The stratigraphy and sedimentology of the Fundy Group (Triassic) of the St. Martins area, New Brunswick. Canadian Journal of Earth Sciences, 22, pp. 1183–1203.

Nance, D. 1985. Alleghenian deformation in the Mispec Group Saint John Harbour, New Brunswick. *In* Current Research, Part A. Geological Survey of Canada, Paper 85-1A, pp. 7–13.

Nance, R.D. 1987. Model for the Precambrian evolution of the Avalon Terrane in southern New Brunswick. Geology, 15, pp. 753–756.

Nance, R.D. and Dallmeyer, R.D. 1993. $^{40}Ar/^{39}Ar$ ages from the Kingston Complex, New Brunswick: evidence for Silurian–Devonian tectonothermal activity and implications for the accretion of the Avalon composite terrane. Journal of Geology, 101, pp. 375–388.

Nance, R.D. and Dallmeyer, R.D. 1994. Structural and $^{40}Ar/^{39}Ar$ mineral age constraints for the tectonothermal evolution of the Green Head Group and Brookville Gneiss, southern New Brunswick, Canada: Implications for the conFiguration of the Avalon composite terrane. Geological Journal, 29, pp. 293–322.

Nance, R.D. and Warner, J.B. 1986. Variscan tectonostratigraphy of the Mispec Group, southern New Brunswick: Structural geometry and deformational history. *In* Current Research, Part A. Geological Survey of Canada, Paper 86-1A, pp. 351–358.

Nance, R.D. and Linnemann, U. 2008. The Rheic Ocean. Origin, evolution, and significance. GSA Today, pp. 1–12.

Neuman, R.B. 1984. Geology and paleobiology of islands in the Iapetus Ocean: Review and implications. Geological Society of America Bulletin, 95**,** pp. 1188–1201.

Olsen, P.E. 1997. Stratigraphic record of the early Mesozoic breakup of Pangea in the Laurasia–Gondwana rift system. Annual Reviews of Earth and Planetary Sciences, 25, pp. 337–401.

Olsen, P. E. and Et-Touhami, M. 2008. Tropical to subtropical syntectonic sedimentation in the Permian to Jurassic Fundy rift basin, Atlantic Canada, in relation to the Moroccan conjugate margin: Field Trip No. 1. Central Atlantic Conjugate Margins Conference Halifax, NovaScotia, Canada,121 p

Olsen, P. E., Whiteside, J. H., Fedak, T. 2005.The Triassic–Jurassic faunal and floral transition in the Fundy Basin, Nova Scotia: Field Trip A7. Geological Association of Canada, Mineralogical Association of Canada, Canadian Society of Petroleum Geologists, Canadian Society of Soil Sciences Joint Meeting, Halifax. Atlantic Geoscience Society Special Publication, 26, 53 p.

Palacios, T., Jensen, S., Barr, S.M., White, C.E., and Miller, R.F. 2011. New biostratigraphical constraints on the lower Cambrian Ratcliffe Brook Formation, southern New Brunswick, Canada, from organic-walled microfossils. Stratigraphy, 8, pp. 45–60.

Papezik, V.S. and Barr, S.M. 1981. The Shelburne dyke, an early Mesozoic diabase dyke in Nova Scotia: Mineralogy, petrology, and regional significance. Canadian Journal of Earth Sciences, 18, pp. 1346–1355.

Papezik, V.S. and Greenough, J.D. 1987. Note on the petrology of North Mountain Basalt from the wildcat oil well Mobil Gulf Chinampas N-37, Bay of Fundy, Canada. Canadian Journal of Earth Sciences, 24, pp. 1255–1260.

Papezik, V.S., Greenough, J.D., Colwell, J.A., and Mallinson, T.J. 1988. North Mountain Basalt from Digby, Nova Scotia: Models for a fissure eruption from stratigraphy and petrochemistry: Canadian Journal of Earth Sciences, 25, pp. 74–83.

Park, A.F., Williams, P.F., Ralser, S., and Léger, A. 1994. Geometry and kinematics of a major crustal shear zone segment in the Appalachians of southern New Brunswick. Canadian Journal of Earth Sciences, 31, pp. 1523–1535.

Patrick, T.O.H. 1964. Exploration of Grand Manan Island for Keevil Mining Group. Geophysical Engineering Surveys, Ltd. New Brunswick Department of Energy and Mines, Mineral Report of Work No. 470333, 17 p.

Pe-Piper, G. and Piper, D.J.W. 1999. Were Jurassic tholeiitic lavas originally widespread in southeastern Canada? A test of the broad terrane hypothesis. Canadian Journal of Earth Sciences, 36, pp. 1509–1516.

Pe-Piper, G. and Wolde, B. 2000. Geochemistry of metavolcanic rocks of the Ross Island and Ingalls Head formations, Grand Manan Island, New Brunswick. Atlantic Geology, 36, pp. 103–116.

Pe-Piper, G., Jansa, L.F., and Lambert, R. St.J. 1992. Early Mesozoic magmatism on the eastern Canadian margin: Petrogenetic and tectonic significance. *In* Mesozoic Magmatism of Eastern North America. *Edited by* J.H. Puffer and P. Ragland. Geological Society of America Special Publication, 268, pp. 13–36.

Philpotts, A.R. and Martello, A. 1986. Diabase feeder dykes for the Mesozoic basalts in southern New England. American Journal of Science, 286, pp. 105–126.

Philpotts, A. R. and Lewis, C. L. 1987. Pipe vesicles - an alternate model for their origin. Geology, 15, pp. 971–974.

Philpotts, A.R. and McHone, J.G.. 2003. Basaltic sills, dykes, and lavas of the Hartford basin, Connecticut, *In* Field Guide for the New England Intercollegiate Geological Conference. *Edited by* J. Brady, J. and J. Cheney. Amherst, Massachusetts, Trip C-2, 31 p.

Philpotts, A.R., Carroll, M., and Hill, J.M. 1996. Crystal-mush compaction and the origin of pegmatitic segregation sheets in a thick flood-basalt flow in the Mesozoic Hartford basin, Ct. Journal of Petrology, 37, pp. 811–836.

Rast, N. 1984. The Alleghenian Orogeny in eastern North America. *In* Variscan Tectonics of the North Atlantic Region. *Edited by* D.H.W. Hutton and D.J. Sanderson. Geological Society of London Special Publication, 14, pp. 197–217.

Rast, N. and Grant, R. 1973. Transatlantic correlation of the Variscan–Appalachian orogeny. American Journal of Science, 273, pp. 572–579.
Roxworth, E. and Signell, R.P. 1998. Construction of digital bathymetry for the Gulf of Maine. Coastal and Marine Geology Program, Woods Hole, Massachusetts. United States Geological Survey, Open File Report 98-801 (online).
Samson, S.D., Barr, S.M. and White, C.E. 2000. Nd isotopic characteristics of terranes within the Avalon Zone southern New Brunswick. Canadian Journal of Earth Sciences, 37, pp. 1039–1052.
Satkoski, A., Barr, S., and Samson, S. 2010. Provenance of Late Neoproterozoic and Cambrian sediments in Avalonia: Constraints from detrital zircon ages and Sm–Nd isotopic compositions in southern New Brunswick, Canada. Journal of Geology, 118, pp. 187–200.
Schaltegger, U., Guex, J., Bartolini, A., Schoene, B., and Ovtcharova, M. 2008. Precise U–Page constraints for end-Triassic mass extinction, its correlation to volcanism and Hettangian post-extinction recovery. Earth and Planetary Science Letters, 267, pp. 266–275.
Schultz, K.J., Stewart, D.B., Tucker, R.D., Pollock, J.C. and Ayuso, R.A. 2008. The Ellsworth terrane, coastal Maine. Geochronology, geochemistry, and Nd–Pd isotopic compositions - Implications for the rifting of Ganderia. Geological Society of America Bulletin, 120, pp. 1134–1158.
Stevens, G.R. 1987. Jurassic basalts of northern Bay of Fundy region, Nova Scotia. *In* Centennial Field Guide - Northeastern Section. *Edited by* D.C. Roy. Geological Society of America, 5, pp. 415–420.
Stringer, P. and Pajari, G.E. 1981. Deformation of pre-Triassic rocks of Grand Manan, New Brunswick. *In* Current Research, Part C. Geological Survey of Canada, Paper 81-1C, pp. 9-15.
Tagg, A.R. and Uchupi, E. 1966. Distribution and geologic structure of Triassic rocks in the Bay of Fundy and the northeastern part of the Gulf of Maine. United States Geological Survey, Professional Paper 550-B, pp. B59–B98.
Tanoli, S.K. and Pickerill, R.K. 1988. Lithostratigraphy of the Cambrian–Lower Ordovician Saint John Group, southern New Brunswick. Canadian Journal of Earth Sciences, 25, pp. 669–690.
Trembath, L.T. 1973. Zeolite mineral assemblage, Grand Manan Island, New Brunswick. *In* Geology of New Brunswick, Field Guide to Excursions. *Edited by* N. Rast. New England Intercollegiate Geological Conference, Department of Geology, University of New Brunswick, Fredericton, New Brunswick, Trip A-1, pp. 1–3.
van Staal, C.R. and Fyffe, L.R. 1995, Gander Zone–New Brunswick. *In* Geology of the Appalachian–Caledonian Orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada, Geology of Canada, No. 6, pp. 216–223.
van Staal, C.R. and de Roo, J.A. 1995. Mid-Paleozoic tectonic evolution of the Appalachian Central Mobile Belt in northern New Brunswick, Canada: Collision, extensional collapse and dextral transpression. *In* Current Perspectives in the Appalachian–Caledonian Orogen *Edited by* J.P. Hibbard, C. R. van Staal, and P. A. Cawood, P.A. Geological Association of Canada Special Paper, 41, pp. 367–389.
van Staal, C.R., Sullivan, R.W., and Whalen, J.B. 1996, Provenance and tectonic history of the Gander Zone in the Caledonian/Appalachian orogen: Implications for the origin and assembly of Avalon. *In* Avalonian and Related peri-Gondwanan Terranes of the Circum-North Atlantic. *Edited by* R.D. Nance and M.D. Thompson. Geological Society of America Special Paper, 304, pp. 347–367.
van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N. 2009. Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians. *In* Ancient Orogens and Modern Analogues. *Edited by* J.B. Murphy, J.D. Keppie, and A.J. Hynes. Geological Society of London Special Publication, 327, p. 271–316.
van Staal, C.R., Barr, S.M., and Murphy, J.B. 2012. Provenance and tectonic evolution of Ganderia: Constraints on the evolution of the Iapetus and Rheic oceans. Geology, 40, pp. 987–990.
Wade, J.A. and Jansa, L.F. 1994. Preliminary interpretation of sub-North Mountain Basalt strata, Dark Harbour, Grand Manan Island, New Brunswick. *In* Geological Survey of Canada, Current Research 1994-E, pp. 227–231.
Wade, J.A., Brown, D.E., Traverse, A., and Fensome, R.A. 1996. The Triassic–Jurassic Fundy Basin, eastern Canada: Regional setting, stratigraphy, and hydrocarbon potential. Atlantic Geology, 32, pp. 189–231.
Westrop, S.R. and Landing, E. 2000. Lower Cambrian (Branchian) trilobites and biostratigraphy of the Hanford Brook Formation, southern New Brunswick. Journal of Paleontology, 74, pp. 858–878.
West, D.P., Jr. and McHone, J.G. 1997. Timing of Early Jurassic “feeder” dyke emplacement, northern Appalachians: Evidence for synchronicity with rift basalts. Geological Society of America, Abstracts with Programs, 29, p. 88.

Whalen, J.B., Jenner, G.A., Currie, K.L., Barr, S.M., Longstaffe, F.J., and Hegner, E. 1994. Geochemical and isotopic characteristics of granitoids of the Avalon Zone, southern New Brunswick: possible evidence for repeated delamination events. Journal of Geology, 102, pp. 269–282.

Whalen, J.B., Jenner, G.A., Longstaffe, F.J., and Hegner, E. 1996a. Nature and evolution of the eastern margin of Iapetus: geochemical and isotopic constraints from Siluro–Devonian granitoid plutons in the New Brunswick Appalachians. Canadian Journal of Earth Sciences, 33, pp. 140–155.

Whalen, J.B., Fyffe, L.R., Longstaffe, F.J., and Jenner, G.A. 1996b. The position and nature of the Gander–Avalon boundary, southern New Brunswick, based on geochemical and isotopic data from granitoid rocks. Canadian Journal of Earth Sciences, 33, pp. 129–139.

White, C.E. and Barr, S.M. 1996. Geology of the Brookville terrane, southern New Brunswick, Canada. *In* Avalonian and related peri-Gondwanan terranes of the Circum-North Atlantic. *Edited by* R.D. Nance and M.D. Thompson. Geological Society of America Special Paper, 304, pp. 133–147.

White, C.E., Barr, S.M., Miller, B.V., and Hamilton, M.A. 2002. Granitoid plutons of the Brookville terrane, southern New Brunswick: Petrology, age, and tectonic setting. Atlantic Geology, 38, pp. 53–74.

White, C.E., Barr, S.M., Reynolds, P.H., Grace, E., and McMullin, D. 2006. The Pocologan Metamorphic Suite: High pressure metamorphism in a Silurian accretionary complex in the Avalon Zone of southern New Brunswick. Canadian Mineralogist, 44, pp. 905–927.

Wolczanski, H.A., Barr, S.M., and Miller, B.V. 2007. Petrology, age, and tectonic setting of The Wolves Pluton: Implications for Appalachian terranes in the western Bay of Fundy region. Atlantic Geology, 43, pp.57–73.